NASA CR-159569

(NASA-CR-159569) INFLIGHT FUEL TANK TEMPERATURE SURVEY DATA Final Report (Boeing Commercial Airplane Co., Seattle) 60 p HC A04/MF A01 CSCL 01C
N79-23940
Unclas
G3/03 22112

In-flight Fuel Tank Temperature Survey Data

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Prepared for
NASA-Lewis Research Center
under contract NAS3-20815

National Aeronautics and Space Administration

1979

1. Report No. NASA CR-159569	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
IN-FLIGHT FUEL TANK TEMPERATURE SURVEY DATA

5. Report Date
May 1979

6. Performing Organization Code

7. Author(s)
A. J. PASION

8. Performing Organization Report No.
D6-48611

9. Performing Organization Name and Address
Boeing Commercial Airplane Company
P. O. Box 3707
Seattle, Wash., 98124

10. Work Unit No.

11. Contract or Grant No.
NAS3-20815

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington D.C., 20546

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Project Manager, Robert Friedman, Airbreathing Engines Division, NASA-Lewis Research Center, Cleveland, Ohio 44135

16. Abstract
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This report contains the statistical summaries of the fuel and air temperature data for twelve different routes and for different aircraft models (B747, B707, DC-10 and DC-8). A table summarizes the minimum fuel, total air and static air temperature expected for a 0.3% probability (one day per year). Minimum fuel temperature extremes agree well with calculated predictions and the minimum fuel temperature does not necessarily equal the minimum total air temperature even for extreme weather, long-range flights.

17. Key Words (Suggested by Author(s))
Aircraft fuels, In-Flight fuel temperatures, Freezing point, Total air temperature, Ambient temperature

18. Distribution Statement
Unclassified-unlimited
Star category 03

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	55	

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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1.0 SUMMARY

This report presents the results of the statistical analysis of the in-flight temperature data recorded by the International Air Transport Association (IATA) member airlines during the winter months of 1977. Over 8000 flights from 18 airlines were coded into a computer to facilitate the analysis of the various recorded parameters.

The principal purposes of analyzing this data are to establish a realistic data base of flight temperatures for use in predicting in-flight fuel temperatures and aid in further verifying Boeing's aircraft fuel tank thermal analyzer computer program. Similar studies have been conducted by several airlines; however, this is the first time data of this magnitude and variety have been analyzed.

This report contains the statistical summaries of the fuel and air temperature data for twelve different routes and four different aircraft models (B747, B707, DC-10, DC-8). A table summarizes the minimum fuel, total air, and static air temperatures expected for an 0.3% probability (one day per year). Minimum fuel temperature extremes agree well with calculated predictions and the minimum fuel temperature does not necessarily equal the minimum total air temperature even for extreme weather, long-range flights.

2.0 INTRODUCTION

World extremes of temperature and other meteorological parameters have been compiled into MIL-STD-210B, *Climatic Extremes for Military Equipment*, a commonly used engineering reference. Figure 1 depicts the cold ambient temperature extremes observed at several levels between the surface and 18 km (60,000 ft). The data were compiled at each altitude regardless of location or time; that is, the given extreme temperature at 9 km (30,000 ft, -72° C) may not have occurred at the same location or year as the extreme temperature at 12 km (40,000 ft, -80° C). These extreme cold ambient temperatures may be expected to occur once in 10, 15, or 20 years, depending upon the lengths of record from which they were obtained. These represent approximately zero probability basis for a given year. Higher probabilities such as the 1, 5, or 10 percentages are constructed for temperature evaluations in a given year. These percentages for the coldest locations at several altitudes are also depicted in figure 1.

For applications requiring an average global altitude definition, the 1% temperatures from figure 1 are sufficient. But, as mentioned, these extreme cold ambient temperatures correspond to extreme temperature locations, and may not correspond or be related to the actual aircraft routes flown. For this reason, a Boeing fuel temperature study (ref. 1) related extreme cold ambient temperatures to global locations. This method was used to establish the extreme in-flight ambient temperatures for various routes and aircraft missions to be used in predicting minimum fuel temperatures during flight.

To aid in verifying the method of predicting the extreme in-flight ambient temperatures, IATA requested their member airlines to record in-flight temperatures for flights during the period of January through May 1977. This report contains statistical summaries of the fuel and air temperature data recorded by the IATA members and also data obtained by one airline for flights during the winter months of 1972 through 1976. The data were analyzed and summarized by the Boeing Commercial Airplane Company under NASA contract NAS3-20815 titled, *Design and Evaluation of Aircraft Heat Source Systems for Use with High-Freezing-Point Fuels.*

The principal purposes of analyzing this data are to establish a realistic data base of flight temperatures for use in predicting in-flight fuel temperatures and to aid in further verifying Boeing's aircraft fuel tank thermal analyzer (AFTTA) computer program. The verification of the AFTTA program will aid in establishing the extreme minimum fuel temperature experienced during flight and thus provide reference data for use in assessing future requirements for jet fuel freezing point specifications. Similar studies have been conucted by several airlines; however, this is the first time data of this magnitude and variety have been analyzed.

3.0 ORGANIZATION OF DATA

The data covers 8,125 flights from 18 airlines. The major contributors were Japan Airlines, Varig, and British Airways, who accounted for 85% of the reported flights. Table 1 lists the contributing airlines and the number of flights for each aircraft type. The flights are separated into 12 routes which are listed in table 2 together with the number of flights per aircraft type. The data for each flight from each airline were coded into a PDP-11/70 computer so that they could be statistically analyzed.

The data from all the airlines except British Airways and Canadian Pacific were recorded on the data sheets supplied by IATA. The parameters coded into the computer are shown in table 3. The data sheets furnished a time history of temperatures and other parameters during each mission. Not all the parameters on each sheet were available for the statistical analysis. Some data sheets contained only partial data and others included values that could not be used in the analysis, either because of ambiguity, omissions, obvious error, or illegibility of the entries.

The data supplied by British Airways were in the form of histograms, giving only the minimum recorded fuel and total air temperatures for each route. The routes which include the British Airways data are noted with an asterisk in table 2. Figures 2 through 40 are computer generated plots of minimum recorded fuel, total air, and static air temperatures. These probability plots represent a convenient visualization of the minimum temperatures encountered during flight. These plots show the probability that a given minimum temperature will occur during a flight. They represent a convenient visualization of the data. Plots are shown for minimum fuel temperature, total air temperature (adiabatic skin temperature), and static air temperature for each type aircraft type where sufficient data were returned to establish a statistical plot. The figures are arranged in the same order as the routes shown in table 2.

Table 1.—Summary of IATA Data

AIRLINE	TOTAL FLIGHTS	FLIGHTS BY AIRCRAFT TYPE			
		747	707	DC–10	DC–8
AER LINGUS	64	21	43	---	---
AIR CANADA	45	18	---	---	27
AIR FRANCE	38	25	13	---	---
AIR INDIA	10	10	---	---	---
AIR NEW ZEALAND	61	---	---	61	---
ALITALIA	131	84	---	21	26
BRANIFF	57	33	---	---	24
BRITISH AIRWAYS	3499	421	1909	1169	---
CANADIAN PACIFIC AIRLINES	18	---	---	---	18
FINN AIR	39	---	---	37	2
IBERIA	34	12	---	17	5
JAPAN AIR LINES	1611	815	---	---	796
NATIONAL	53	---	---	53	---
SABENA	76	---	---	76	---
SOUTH AFRICAN AIRLINES	18	18	---	---	---
SCANDINAVIAN AIRLINES	148	---	---	132	16
VARIG	2192	---	1701	491	---
ZAMBIA	31	---	31	---	---
TOTALS	8125	1457	3697	2057	914

Table 2.—Aircraft/Route/Flight Summary

ROUTE	747	707	DC–10	DC–8	TOTAL
	NUMBER OF FLIGHTS				
POLAR	635*	465*	1236*	74	2410
NORTH ATLANTIC	137	1321*	103	44	1605
ANCHORAGE – TOKYO	292	98	28	500	918
JAPAN – MOSCOW	----	178*	----	167	345
WESTERN U.S. – TOKYO	321	68	----	----	389
SOUTH AMERICA – EUROPE	17	500	333	----	850
EASTERN NORTH AMERICA – SOUTH AMERICA	----	445	176	14	635
WESTERN NORTH AMERICA – SOUTH AMERICA	----	289	1	10	300
SOUTH AMERICA – AFRICA	----	141	----	----	141
EUROPE – MIDDLE EAST	6	----	58	3	67
EUROPE – AFRICA	13	30	29	7	79
PACIFIC	33	----	57	----	90

* Includes Data Supplied by British Airways

Table 3.—Recorded Flight Parameters

Date	Fuel tank temperature
Flight number	Static air temperature
Aircraft type	Total air temperature
Departure airport	Pilot's indicated airspeed
Arrival airport	Pilot's mach number
Time	Co-pilot's indicated airspeed
Altitude	Co-pilot's mach number
	Position (co-ordinates)

4.0 RESULTS AND DISCUSSION

The statistical data presented in figures 2 through 40 are based on the data she[illegible] supplied by IATA and the data provided by British Airways and Canadian Pacific Airways. The points shown on each of the figures are the actual recorded data points and have not been corrected to a common altitude, Mach number, or time of day. A statistical analysis based on the minimum recorded fuel, total air, and static air temperatures for each flight was conducted for each combination of route and aircraft type. The points represent the statistical data and the solid line is a representation of a normal distribution based on a mean and a standard deviation established from the data points.

Each route and aircraft type combination has a plot for the minimum recorded fuel, minimum recorded total air and minimum recorded static air temperatures except those route and aircraft type combinations which include the British Airways data. For these route/aircraft combinations only the minimum recorded fuel and total air temperatures are provided because the data made available by British Airways did not include static air temperatures.

Table 4 shows a summary of the minimum temperatures on each route for a 0.3% probability (one day per year) and that the coldest routes appear to be Polar, Anchorage-Tokyo, Japan-Moscow, Western U.S.-Tokyo and Europe-Africa. The 0.3% probability minimum temperatures are based on the normal distribution extrapolated as necessary. In some cases, deviations of low probability data from the normal distribution are evident in the figures. Several routes, or route/aircraft combinations, involved limited numbers of flights such as Europe-Middle East, and the statistical extrapolation to 0.3% probability may be questionable. In a few cases the use of a normal distribution gives a minimum fuel temperature lower than the minimum total air temperature, an impossible condition. The deviation of the normal distribution line from the data points is apparent from these situations (Europe-Middle East and Europe-Africa). In general the coldest routes were those within the Northern Hemisphere for the winter data survey.

It is unreasonable to assume that the extreme cold ambient temperatures as defined by MIL-STD-210B will occur throughout the length of a flight. In order to establish a reasonable extreme cold temperature that might be encountered by aircraft during a flight, a method which relates extreme cold ambient temperatures at altitude to global location was formulated, shown in reference 1. This method provided cold ambient temperature information for 9 km and 12 km altitudes on two polar projection charts, displayed in figures 41 and 42. This was accomplished by obtaining basic data from a Naval Weather Service Atlas (ref. 2). These data consist of average and standard temperature data for several altitudes derived from temperatures measured globally during each month of the year. The January average temperatures minus two standard deviations were used to construct new charts of extreme temperatures versus global position. These temperature extremes approximate an annual 0.3% probability (one day per year) of occurence and are plotted as isotherms in figures 41 and 42.

Superimposing the routes flown by various airlines on these charts, it was found that several

Table 4.—Summary of Minimum Recorded Temperatures

ROUTE	MINIMUM TEMPERATURES (0.3% PROBABILITY) (°C)				
	ALL FTEMP TAT SAT *	747 FTEMP TAT SAT	707 FTEMP TAT SAT	DC–10 FTEMP TAT SAT	DC–8 FTEMP TAT SAT
POLAR	-41.5	-43.0	-44.0	-38.5	-43.0
	-46.0	-46.0	-49.0	-43.0	-48.0
	**	**	**	**	-79.5
NORTH ATLANTIC	-38.0	-38.0	-37.5	-35.5	-46.0
	-47.5	-44.5	-48.0	-41.5	-51.0
	**	-69.0	**	-68.5	-71.5
ANCHORAGE–TOKYO	[illegible]	-31.5	-35.0	-40.0	-39.0
	-44.0	-41.0	-40.0	-41.0	-44.0
	-72.0	-70.0	-71.0	-70.5	-73.0
JAPAN–MOSCOW	-43.0	——	-44.5	——	-41.5
	-49.0	——	-53.0	——	-45.0
	**	——	**	——	-71.5
WESTERN U.S.–TOKYO	-36.5	-36.0	-36.0	——	——
	-44.0	-43.0	-44.0	——	——
	-72.5	-72.5	-70.0	——	——
SOUTH AMERICA–EUROPE	-36.0	——	-32.5	-32.0	——
	-38.0	——	-38.0	-35.5	——
	-65.0	——	-65.0	-63.5	——
EASTERN NORTH AMERICA–SOUTH AMERICA	-36.0	——	-31.5	-27.5	——
	-38.0	——	-40.0	-31.0	——
	-62.5	——	-61.5	-60.0	——
WESTERN NORTH AMERICA–SOUTH AMERICA	-33.0	——	-33.0	——	——
	-34.5	——	-34.5	——	——
	-63.0	——	-61.5	——	——
SOUTH AMERICA–AFRICA	-35.5	——	-35.5	——	——
	-37.5	——	-37.5	——	——
	-64.0	——	-64.0	——	——
EUROPE–MIDDLE EAST	-51.0	——	——	-41.5	——
	-44.0	——	——	-44.5	——
	66.0	——	——	-66.0	——
EUROPE–AFRICA	-43.5	——	-38.0	-46.0	——
	-41.5	——	-44.0	-39.0	——
	-70.0	——	-73.0	-68.0	——
PACIFIC	-30.0	-31.0	——	-27.0	——
	-45.0	-44.0	——	-37.0	——
	-70.0	-69.5	——	-61.5	——

* FTEMP = Fuel Temperature
TAT = Total Air Temperature (Adiabatic Skin Temperature)
SAT = Static Air Temperature

** SAT Data Not Supplied by British Airways long-range flights of the world scheduled airlines pass over or near to the site of the coldest temperatures at 12 km in the Northern Hemisphere. The coldest temperature to be expected on a one-day-per-year probability at the coldest location is -72° C (-97.6° F).

Ambient air temperature-range flight profiles corresponding to these cold ambient temperature extremes were constructed for various ranges and these profiles are shown in figure 43. These profiles were also used for the fuel freezing point study reported in reference 3. This figure shows that the duration of the minimum ambient temperatures is short relative to the length of the flight and thus the probability of the fuel temperature equaling the minimum total air temperature experienced during flight is very small. Table 4 shows that the minimum total air temperature is considerably above the minimum fuel temperature. This indicates that the minimum fuel temperature cannot be predicted from the minimum total air temperature or the minimum static air temperature alone. Rather it must be calculated based on the total air temperature, time histories for the aircraft mission, and the duration and location of the minimum static air temperature encountered. It should be noted that the 0.3% probability minimum static air temperature in table 4 agrees very well with the -72° C minimum static air temperature predicted in figure 43.

The reduced data were also used to aid in further verifying Boeing's aircraft fuel tank thermal analyzer (AFTTA) computer program. This program was developed to calculate the aircraft's in-flight fuel tank temperature given the flight condition, static air temperatures, and fuel tank geometry.

Ten flights from each route were randomly picked to compare AFTTA's predicted fuel tank temperatures with the recorded fuel temperatures. This comparison was conducted for only the 747 and 707 since the tank geometry for the DC-8 and DC-10 was not available. Typical results are shown in figures 44 and 45.

These figures represent a flight for each aircraft. The recorded static ambient temperatures, Mach numbers, altitude, and flight time were coded into the AFTTA computer program. The resulting predicted fuel tank temperatures and the recorded fuel tank temperature for the same flight are shown in figures 44 and 45.

The results of this comparison indicated that the fuel tank temperatures predicted by AFTTA were within a mean absolute deviation of 3° C of the recorded temperature during the cruise portion of the flights. Furthermore, the predicted minimum fuel tank temperatures for each flight were consistently lower than the minimum recorded fuel temperatures.

The difference between the predicted and recorded fuel tank temperatures could have been minimized if the fuel load and fuel management procedures were known. These values had to be assumed based on the length of the flight and the normal operating procedures for the aircraft. Nevertheless, a 3° C difference is considered satisfactory and the errors seem to be on the conservative side since the predicted minimum fuel tank temperatures were consistently lower. This apparent verification of the AFTTA program has further increased the validity of Boeing's predicted minimum expected in-flight fuel temperature. These predicted fuel temperatures based on a 0.3% (one day per year) probability cold ambient temperature were -43° C and -46° C for the 747 and 707 respectively, ref. 1. These temperatures compare favorably with the 0.3% probability minimum fuel temperature established by the IATA data in table 4.

5.0 CONCLUDING REMARKS

This report presented the results of the statistical analysis of the in-flight temperature data recorded by the International Air-Transport Association (IATA) member airlines during the winter months of 1977. Over 8 000 flights from 18 airlines were coded into a computer to facilitate the analysis of the various recorded parameters. The data have been assembled statistically to determine a minimum fuel temperature for a 0.3% probability. The extreme minimum fuel temperature is generally above the minimum total air temperature. This condition exists because the duration of the minimum static air temperature encountered during flight is relatively short. The report presents the data to establish a realistic data base for flight temperature predictions without resorting to an assumption that the minimum fuel and air temperatures are identical. A comparison with the in-flight fuel temperatures to a Boeing predicted fuel temperature shows good agreement and gives confidence to the convenient method for establishing fuel temperature limits.

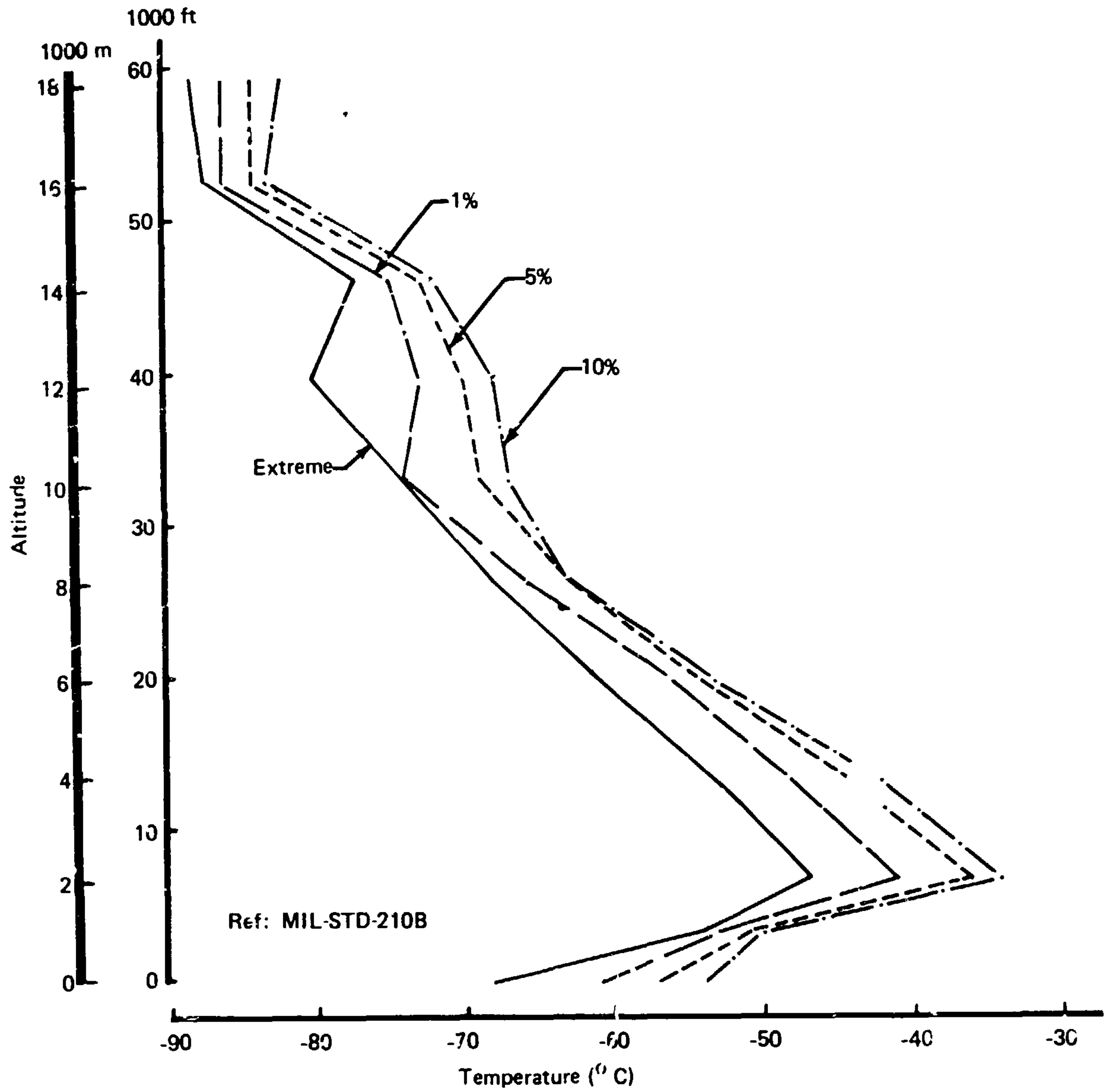
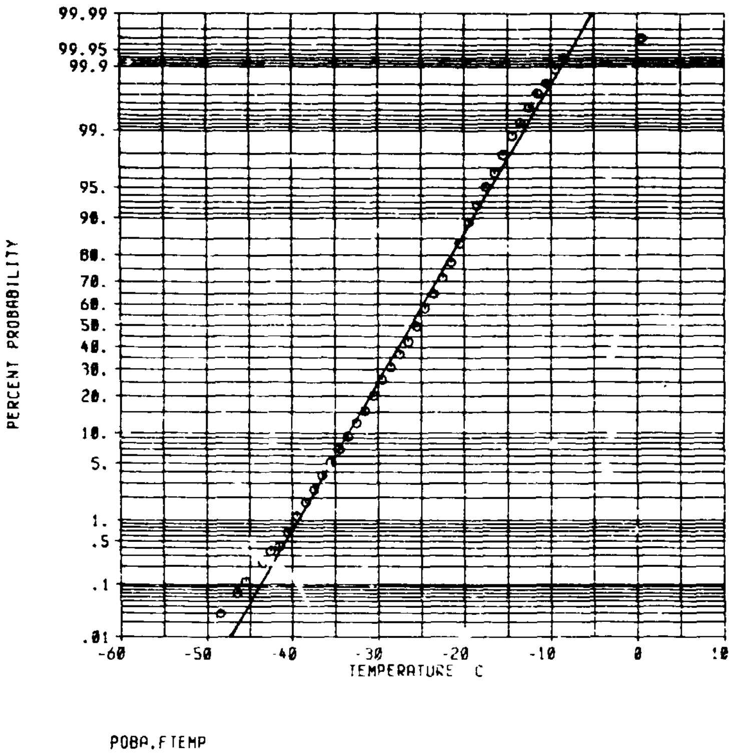


Figure 1.—World Wide Extremes of Air Temperature

MINIMUM RECORDED FUEL TEMPERATURE



MINIMUM RECORDED TOTAL AIR TEMPERATURE

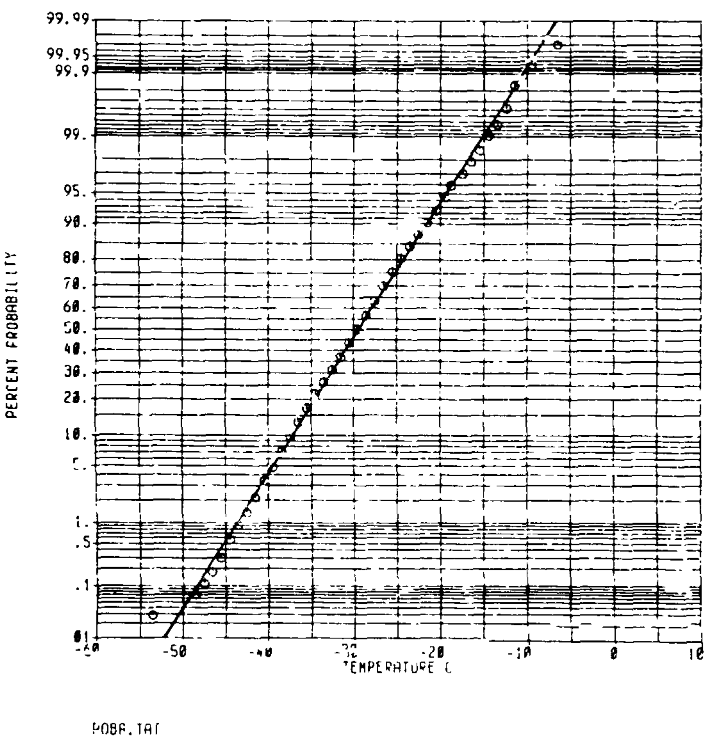
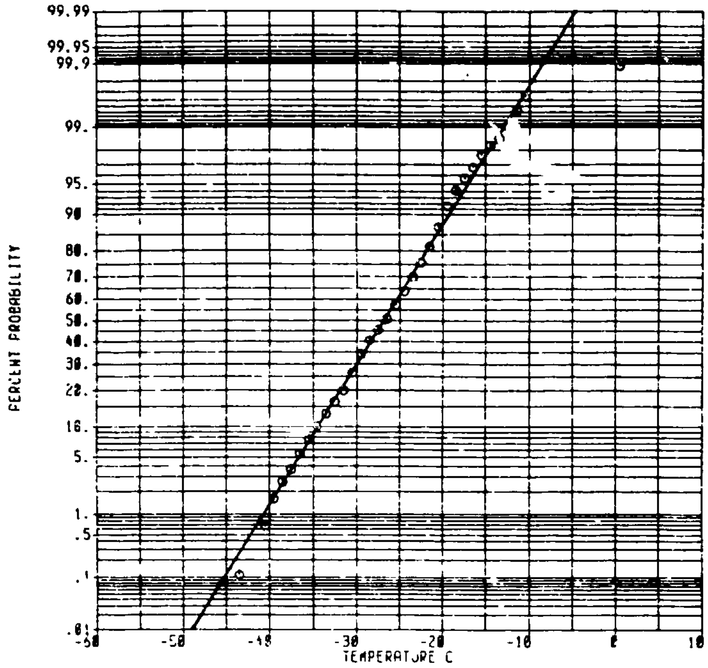


Figure 2.—All Polar Flights

MINIMUM RECORDED FUEL TEMPERATURE



P0BA747.FTEMP

MINIMUM RECORDED TOTAL AIR TEMPERATURE

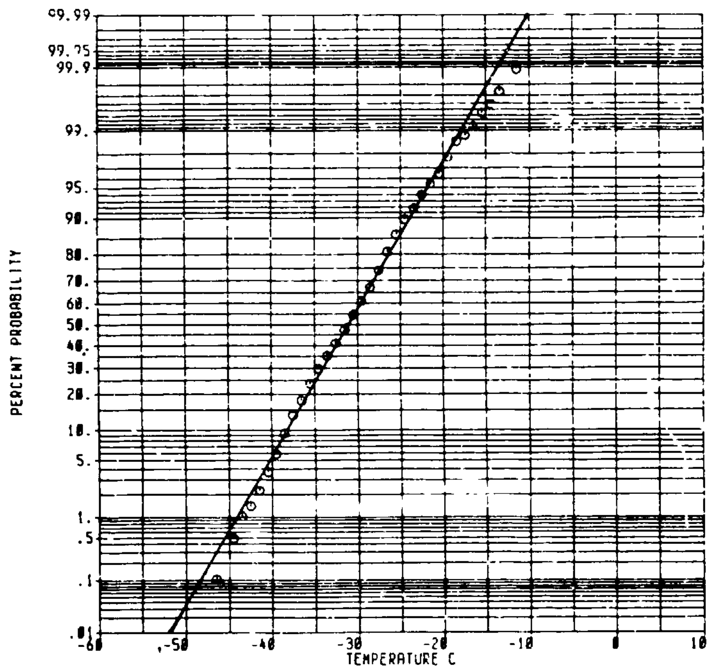


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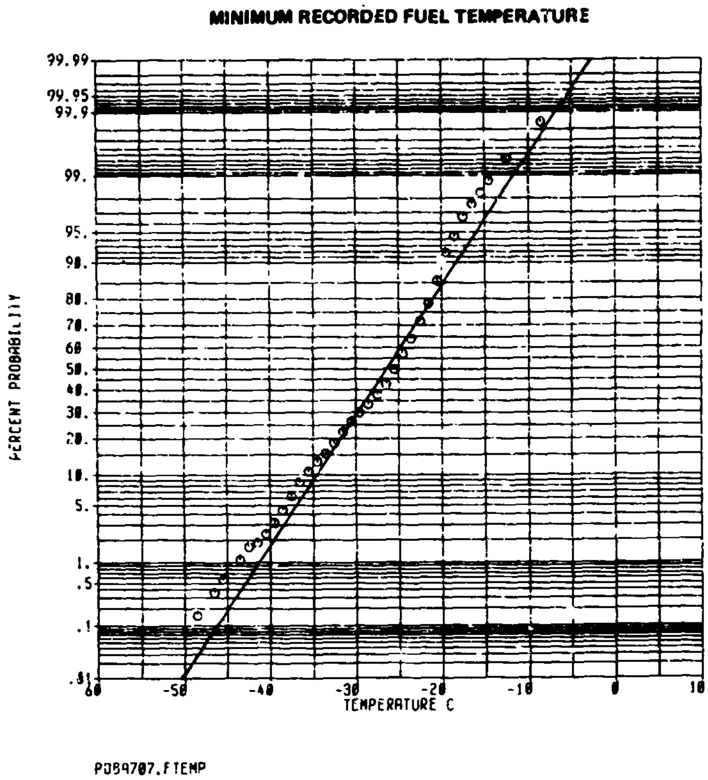
Figure 3.—747 Polar Flights



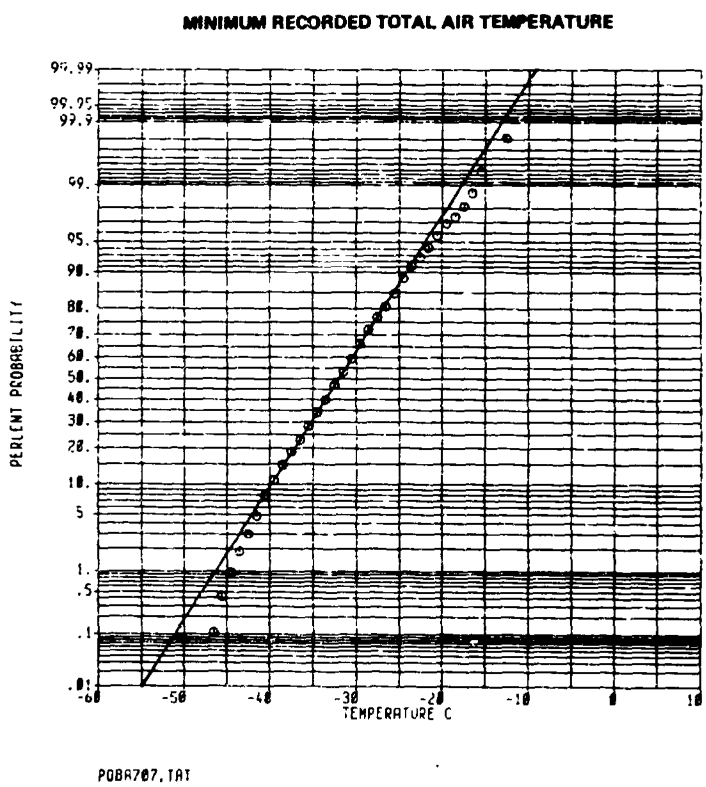
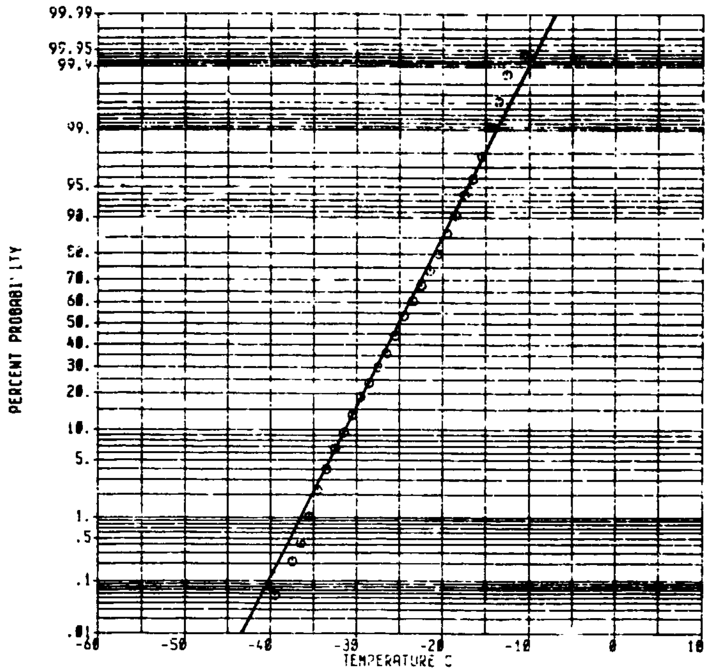


Figure 4.—707 Polar Flights

MINIMUM RECORDED FUEL TEMPERATURE



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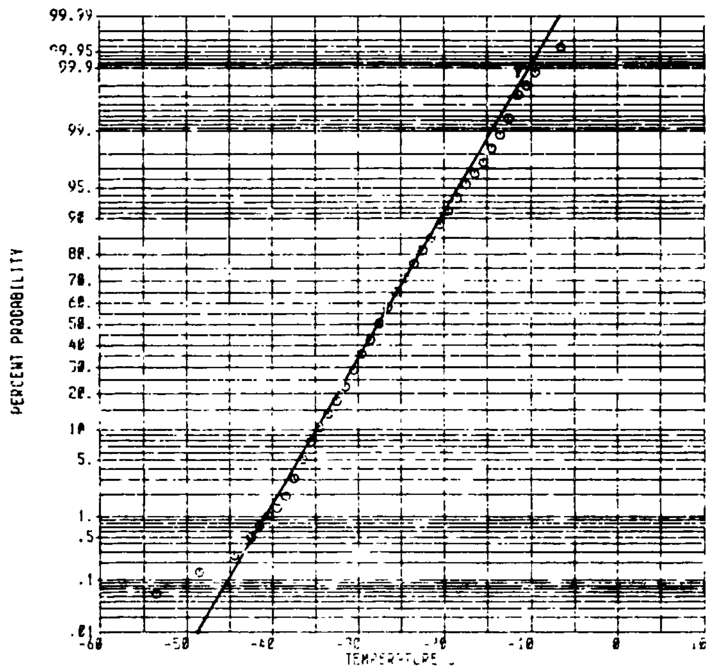
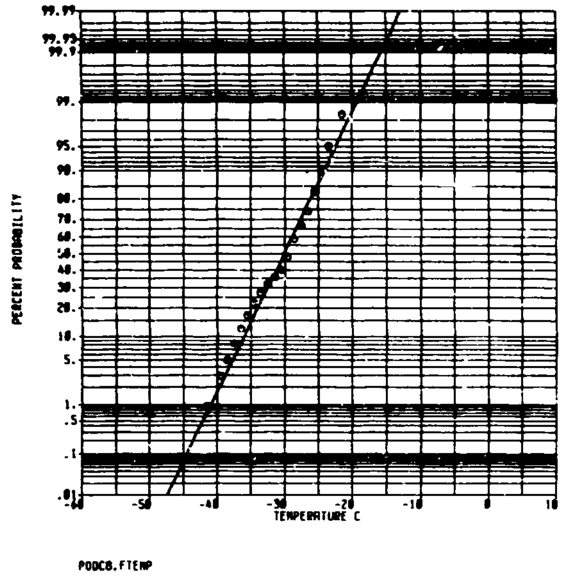
MINIMUM RECORDED TOTAL AIR TEMPERATURE



POBADC0.TAT

Figure 5.—DC-10 Polar Flights

MINIMUM RECORDED FUEL TEMPERATURE



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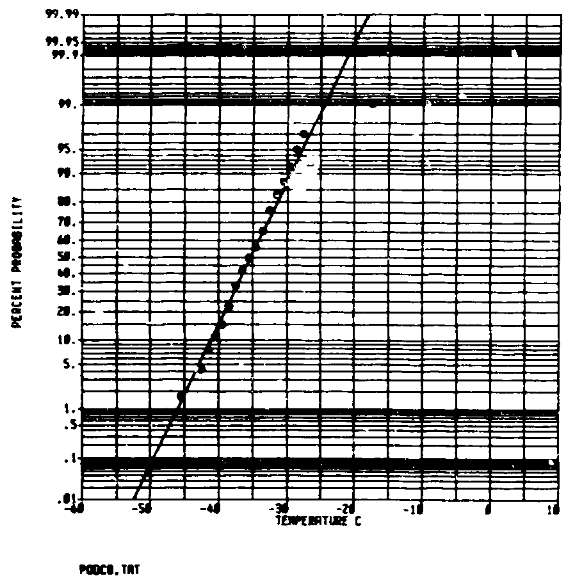


MINIMUM RECORDED STATIC AIR TEMPERATURE

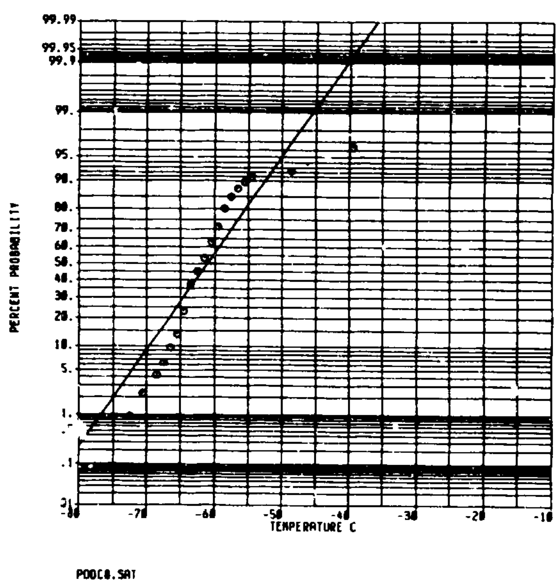
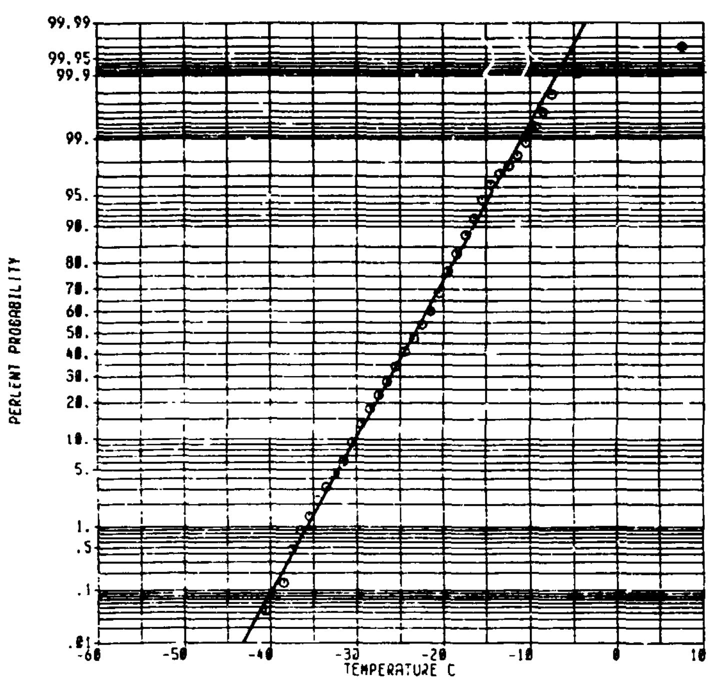


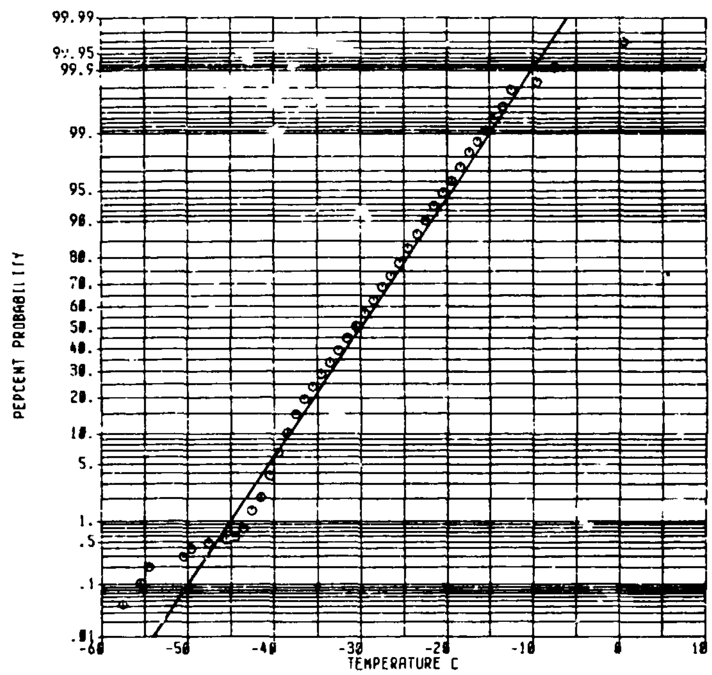
Figure 6.—DC-8 Polar Flights

MINIMUM RECORDED FUEL TEMPERATURE



NABA,FTEMP

MINIMUM RECORDED TOTAL AIR TEMPERATURE



NABA,TAT

Figure 7.—All North Atlantic Flights

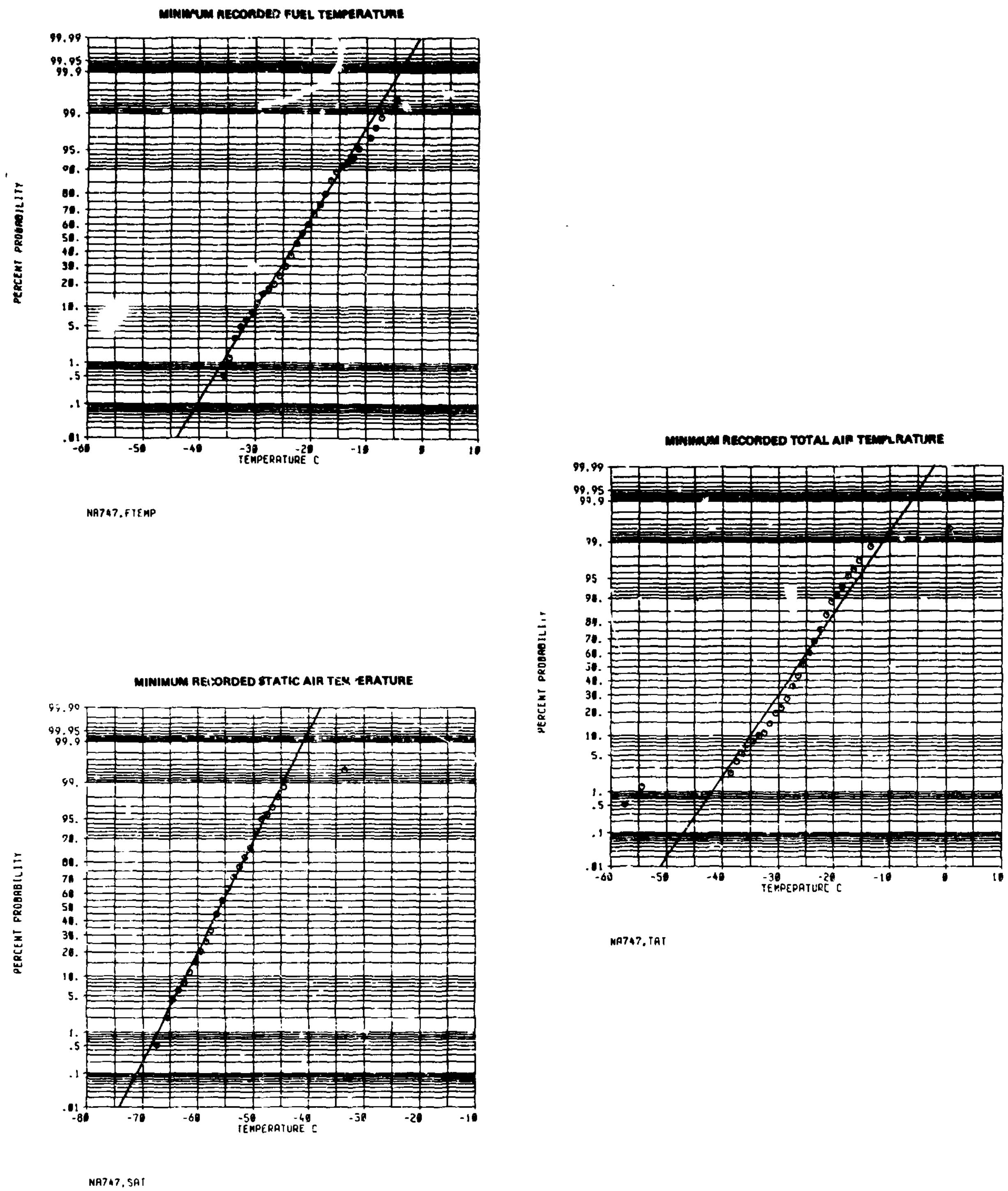


Figure 8.—747 North Atlantic Flights

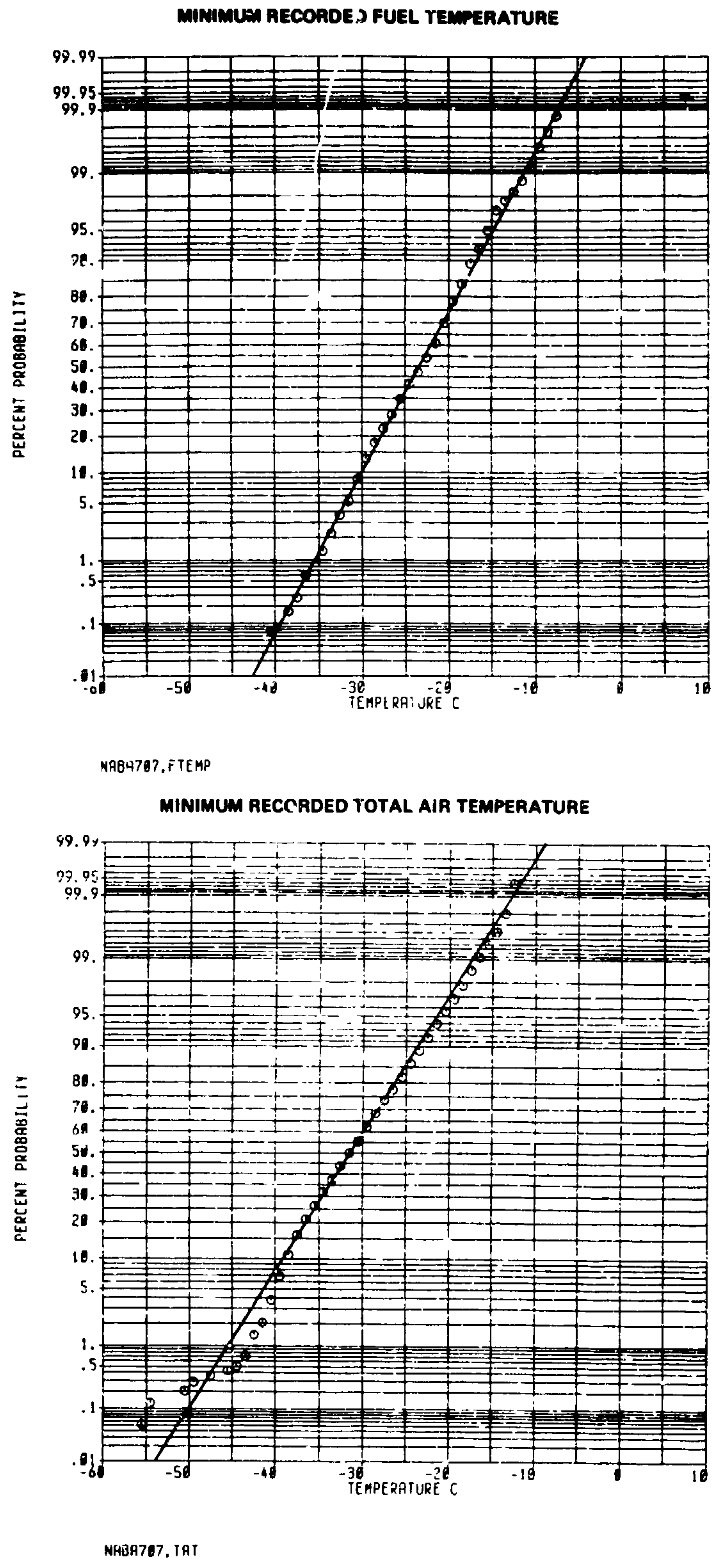
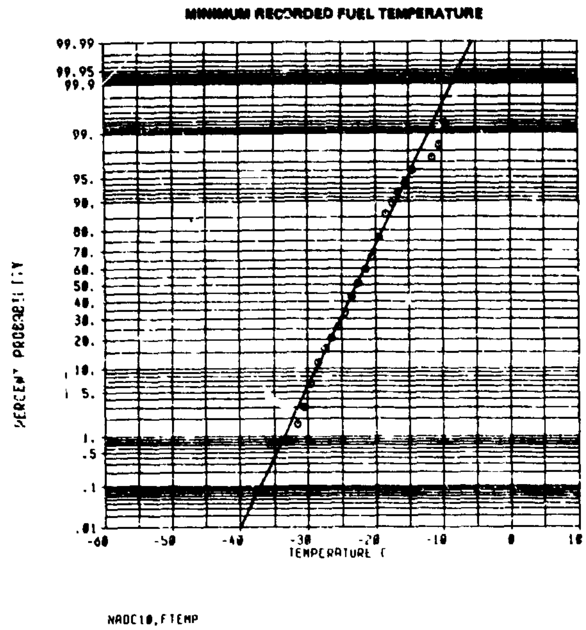
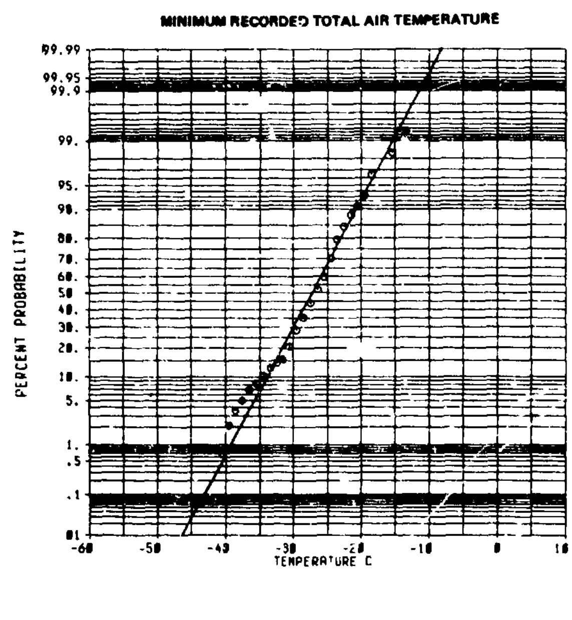


Figure 9.—707 North Atlantic Flights





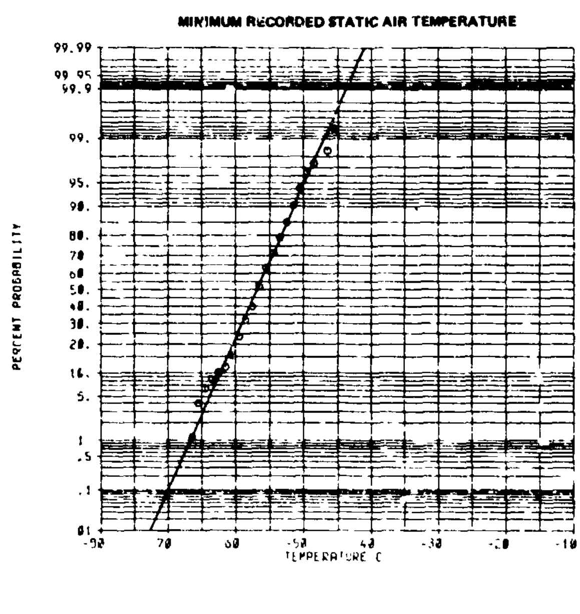
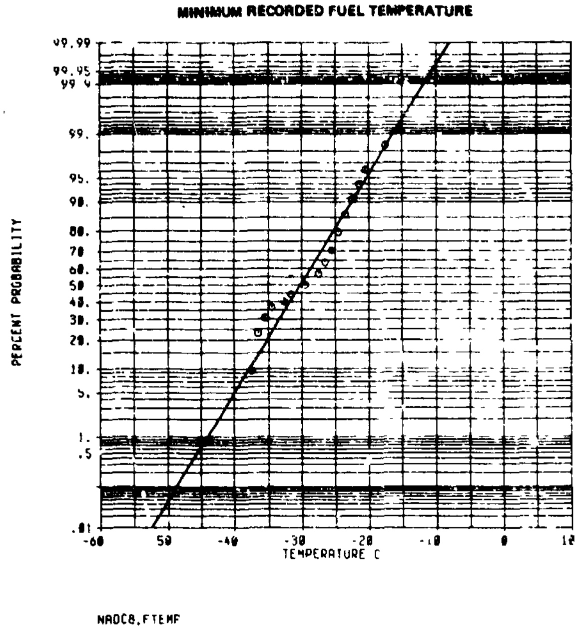
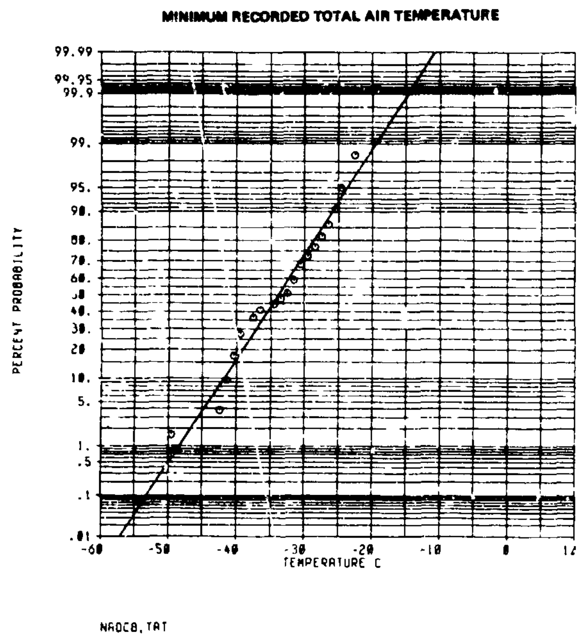


Figure 10.—DC-10 North Atlantic Flights





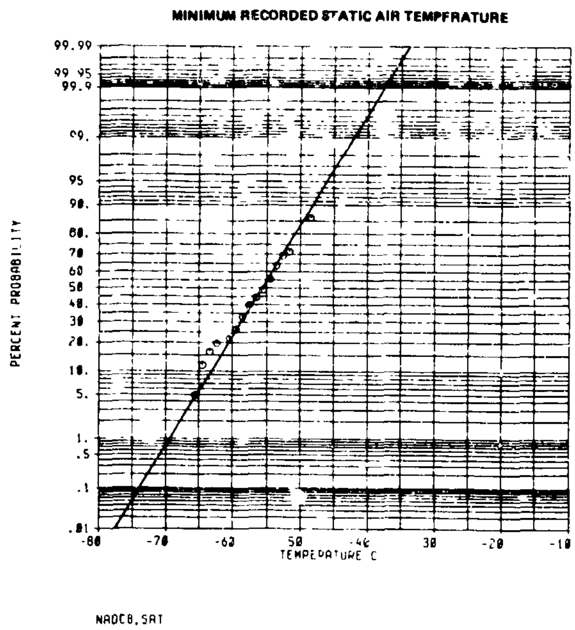
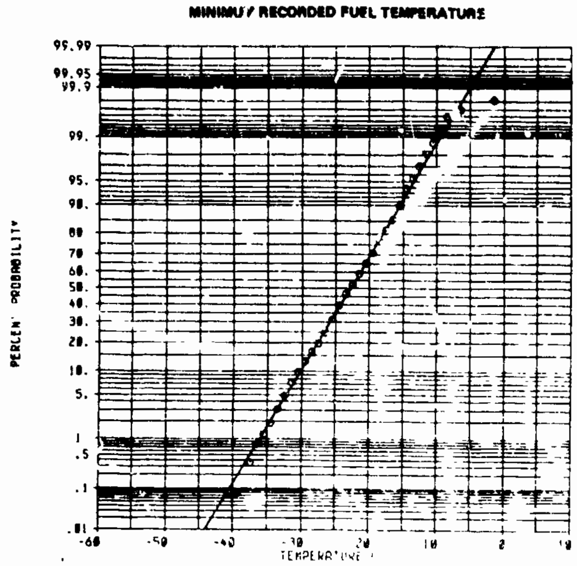
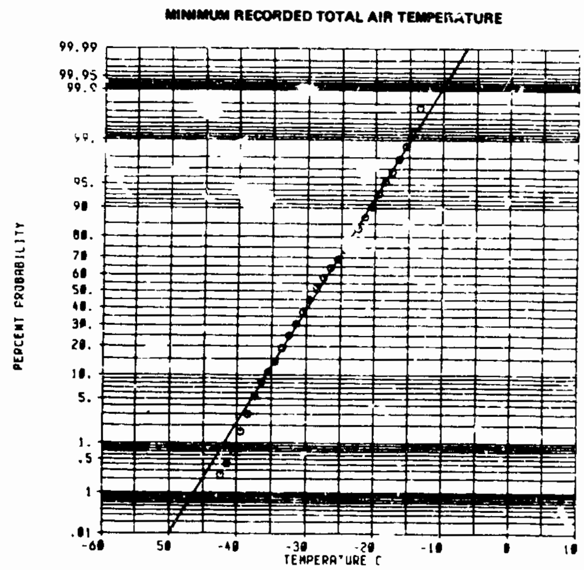


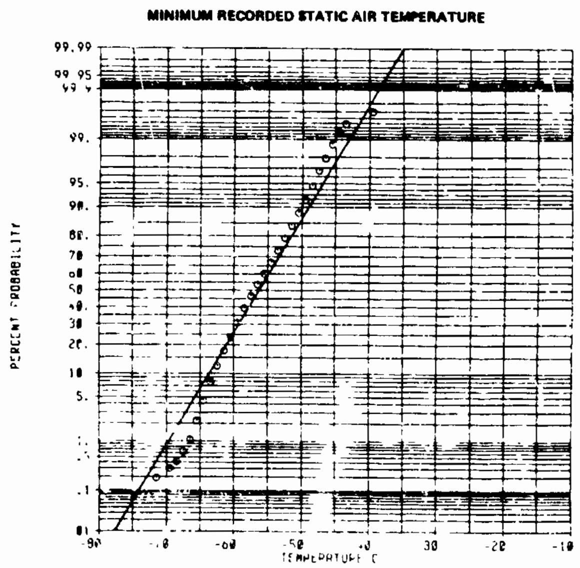
Figure 11.—DC-8 North Atlantic Flights



ANCTYO.FTEMP



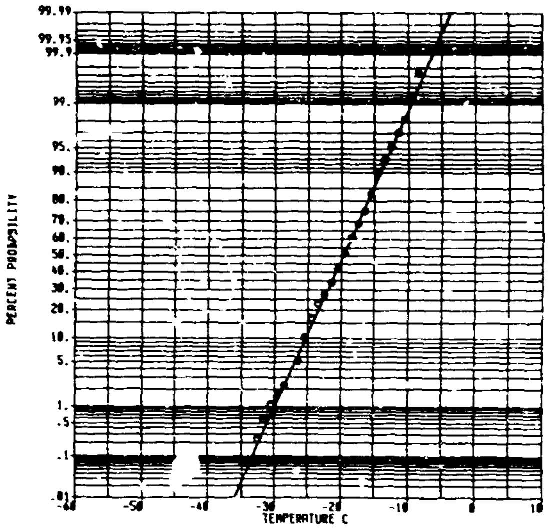
ANCTYO.TAT



ANCTYO.SAT

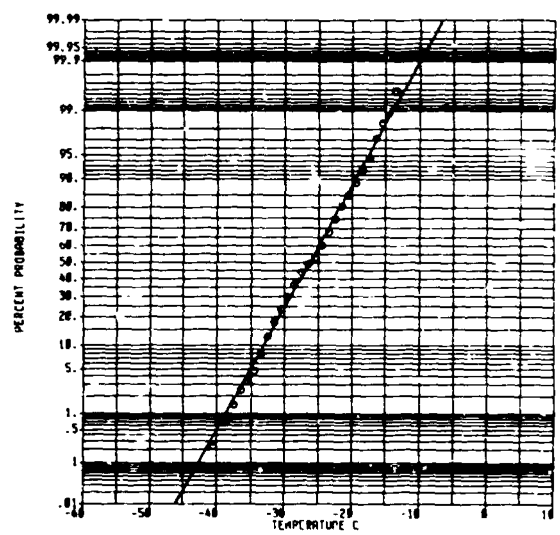
Figure 12.—All Anchorage—Tokyo Flights

MINIMUM RECORDED FUEL TEMPERATURE



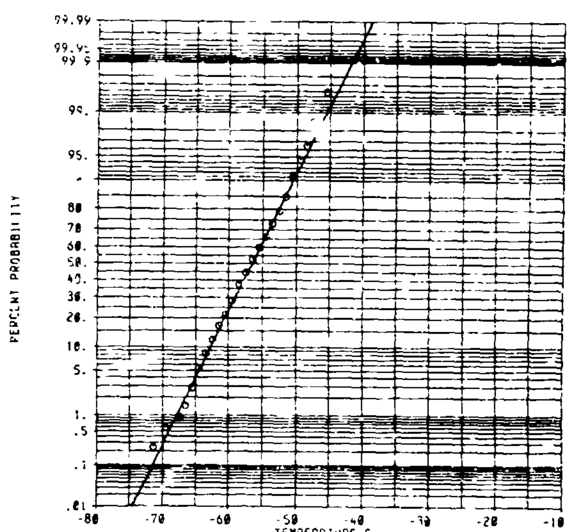
AT747.FTEMP

MINIMUM RECORDED TOTAL AIR TEMPERATURE



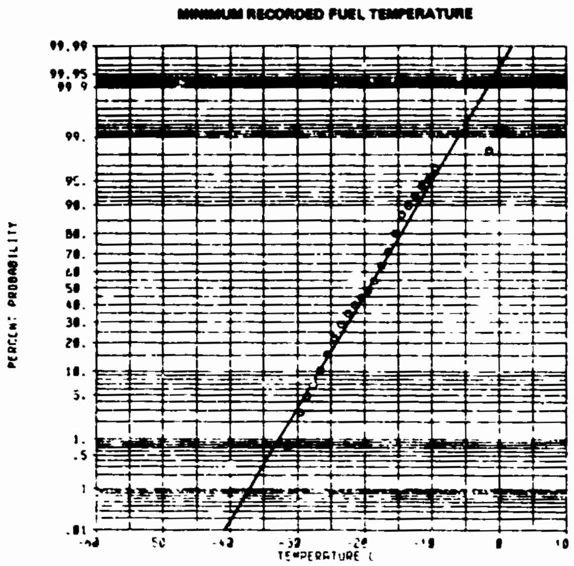
AT747.TAT

MINIMUM RECORDED STATIC AIR TEMPERATURE

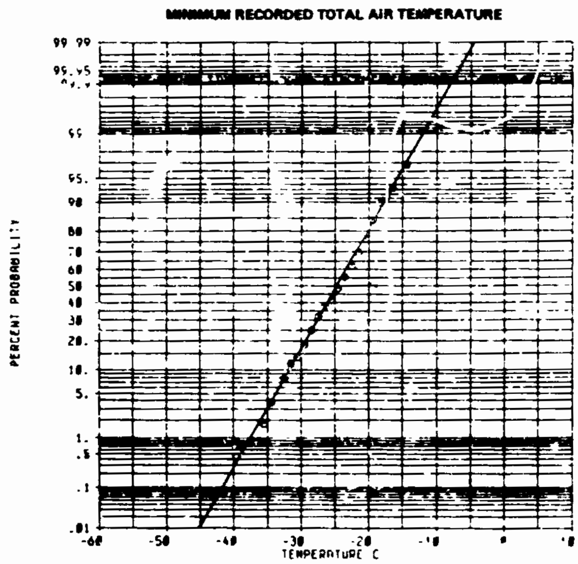


AT747.SAT

Figure 13.—747 Anchorage—Tokyo Flights

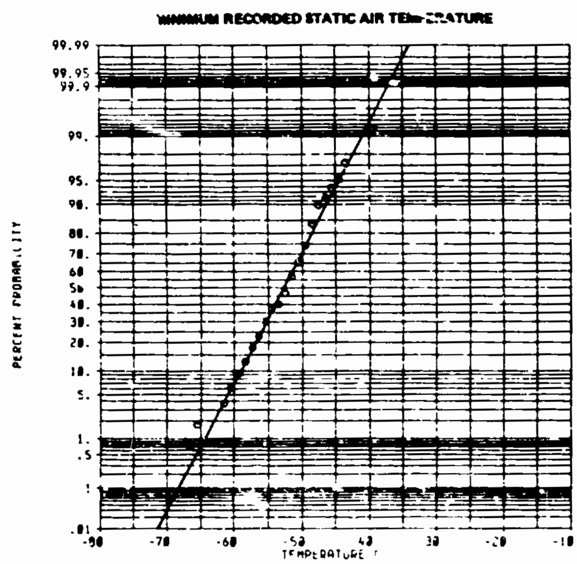


RT707.FTEMP



RT707.TAT

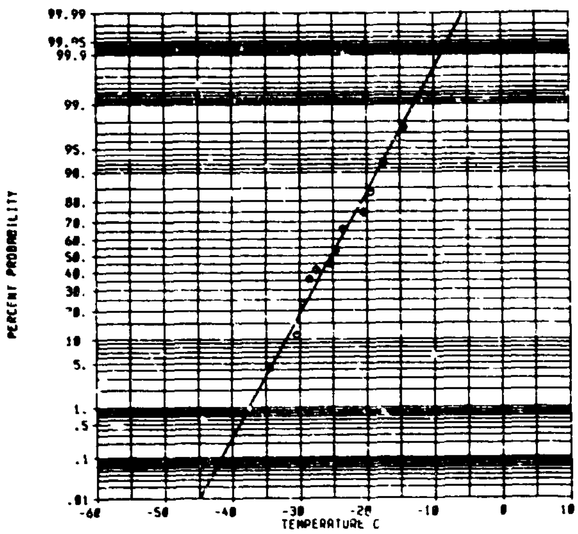
FIGURE 32



RT707.SAT

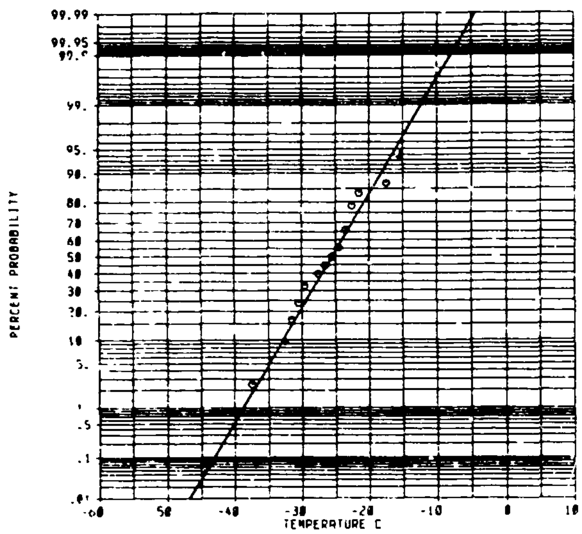
Figure 14.—707 Anchorage—Tokyo Flights

MINIMUM RECORDED FUEL TEMPERATURE



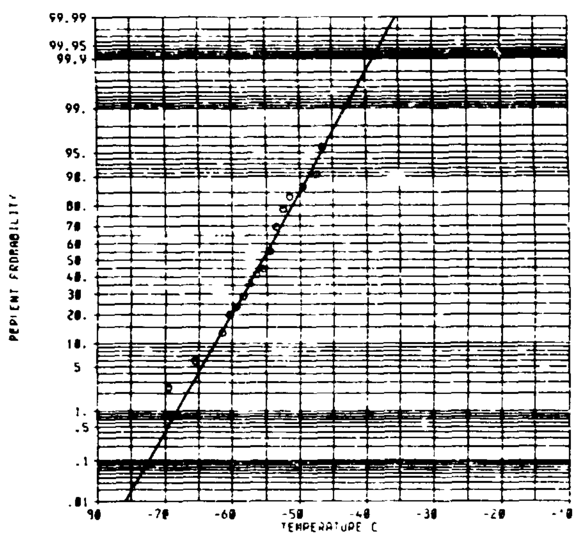
ATDC10.FTEMP

MINIMUM RECORDED TOTAL AIR TEMPERATURE



ATDC10.TA.

MINIMUM RECORDED STATIC AIR TEMPERATURE



ATDC10.SAT

Figure 15.—DC-10 Anchorage—Tokyo Flights

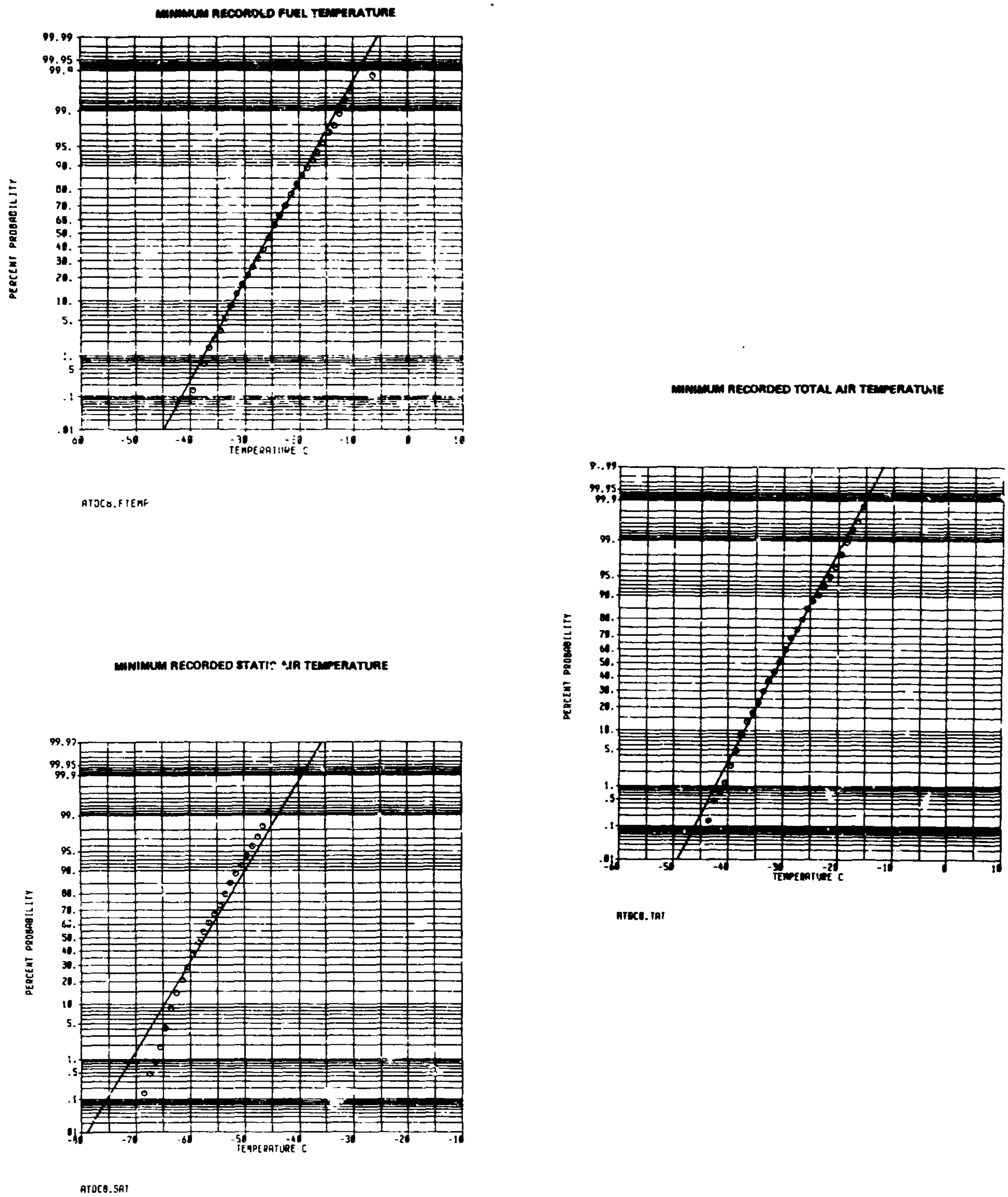
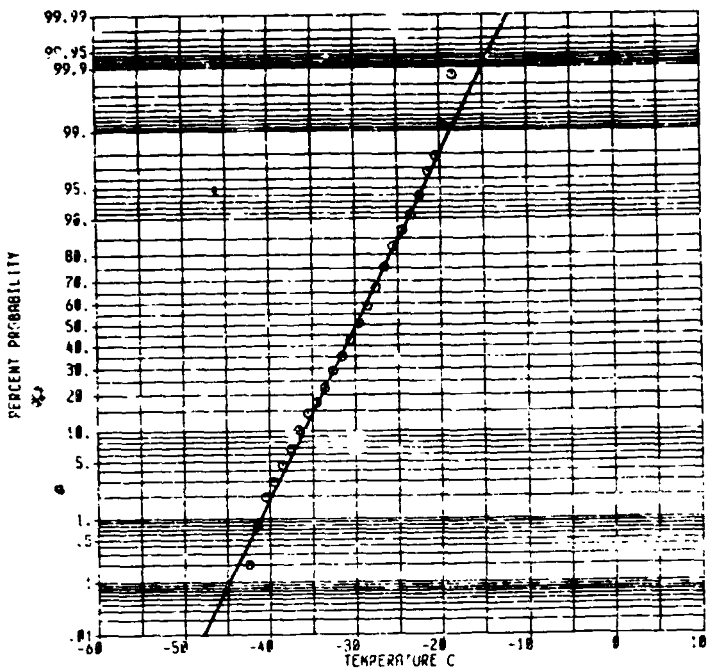


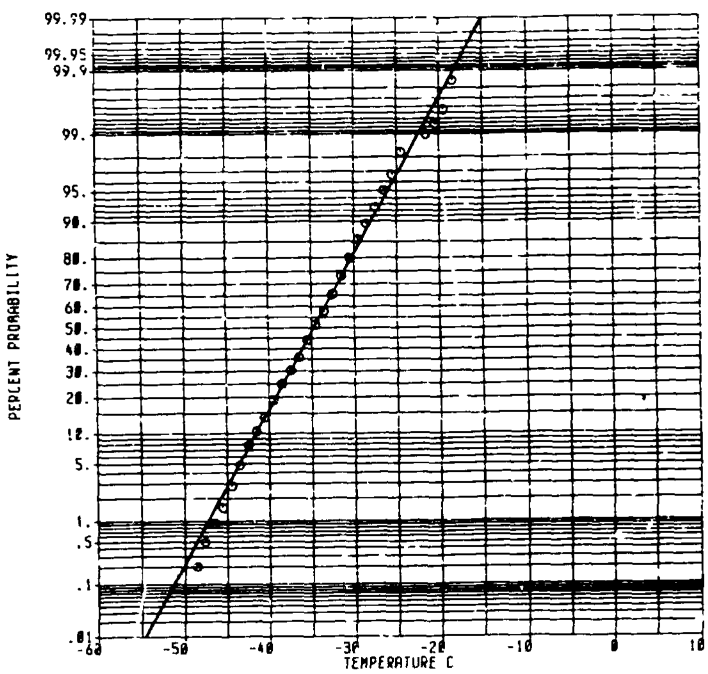
Figure 16.—DC-8 Anchorage—Tokyo Flights

MINIMUM RECORDED FUEL TEMPERATURE



JMBA.FTEMP

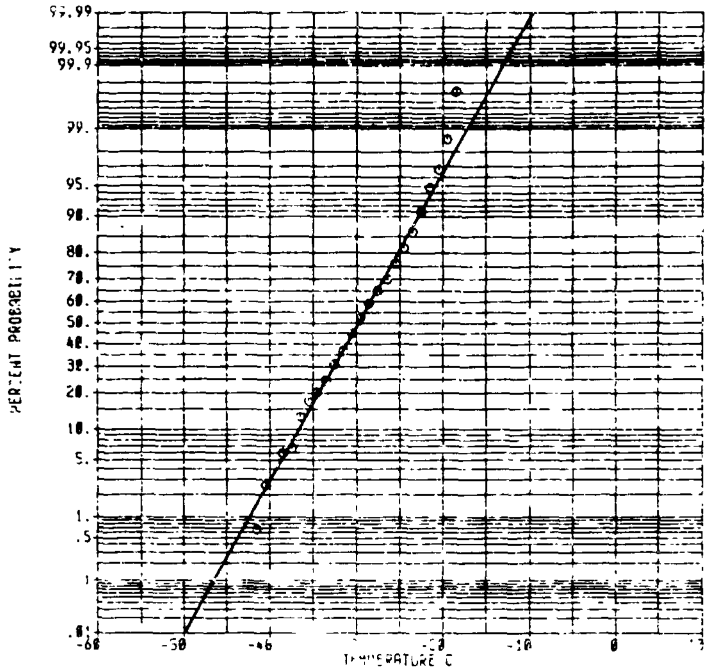
MINIMUM RECORDED TOTAL AIR TEMPERATURE



JMBA.TAT

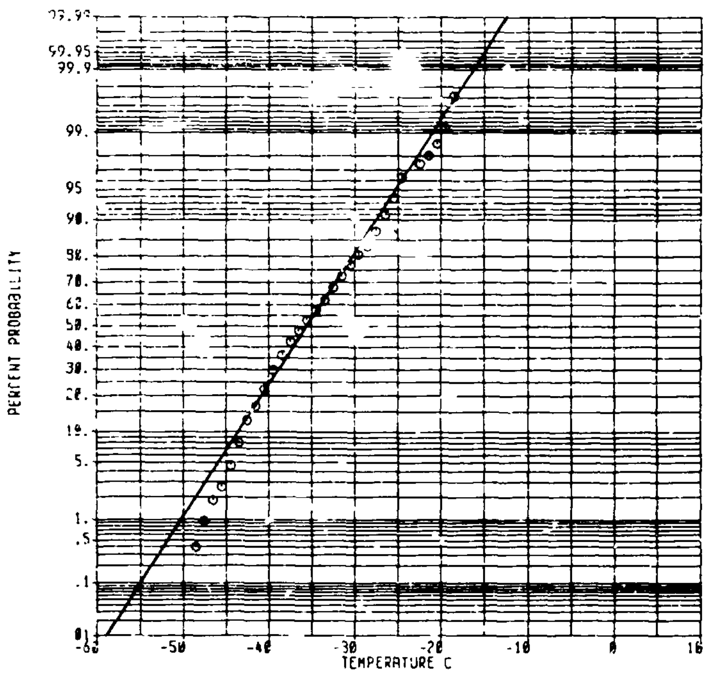
Figure 17.–All Japan–Moscow Flights

MINIMUM RECORDED FUEL TEMPERATURE



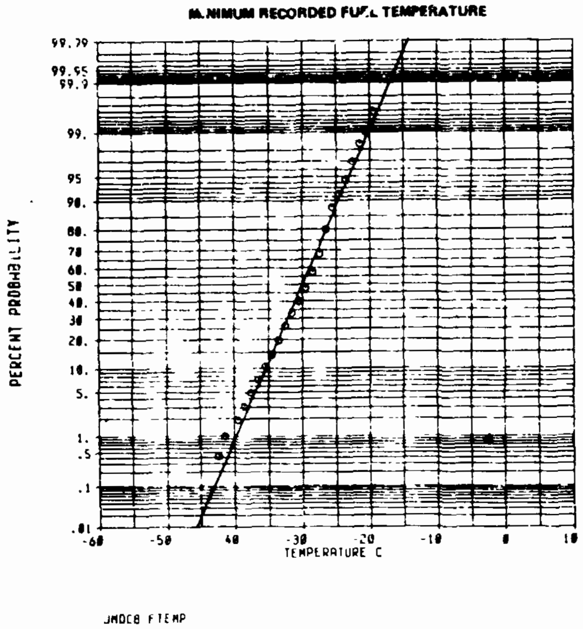
JMBA707.FTEMP

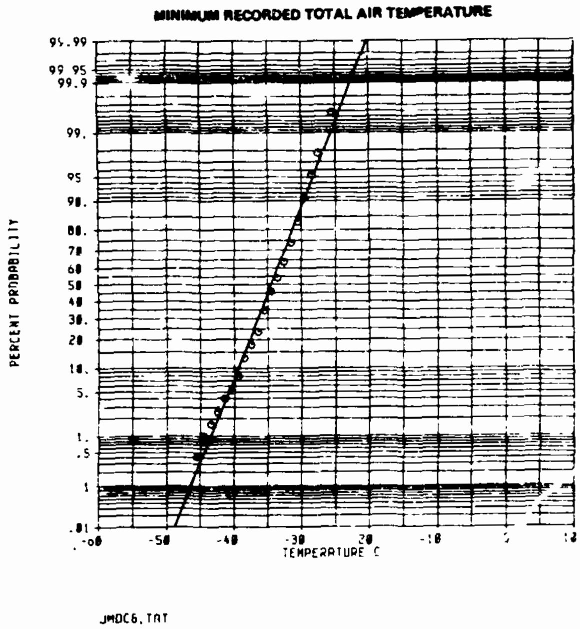
MINIMUM RECORDED TOTAL AIR TEMPERATURE



JMBA707.TAT

Figure 18.—707 Japan—Moscow Flights





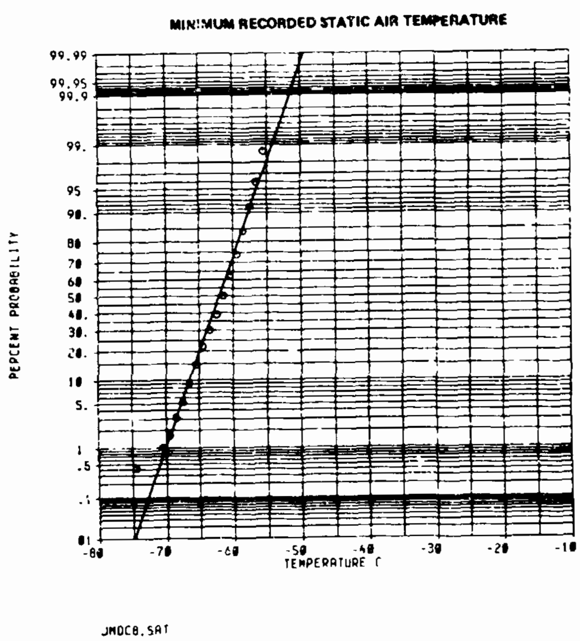
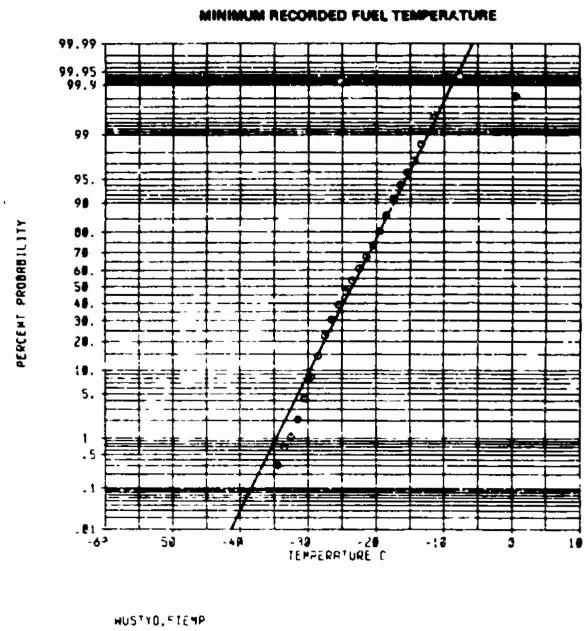
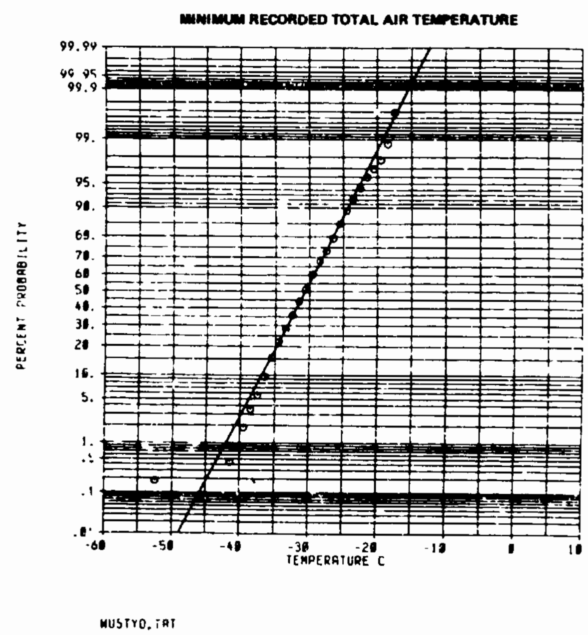


Figure 19.—DC-8 Japan—Moscow Flights





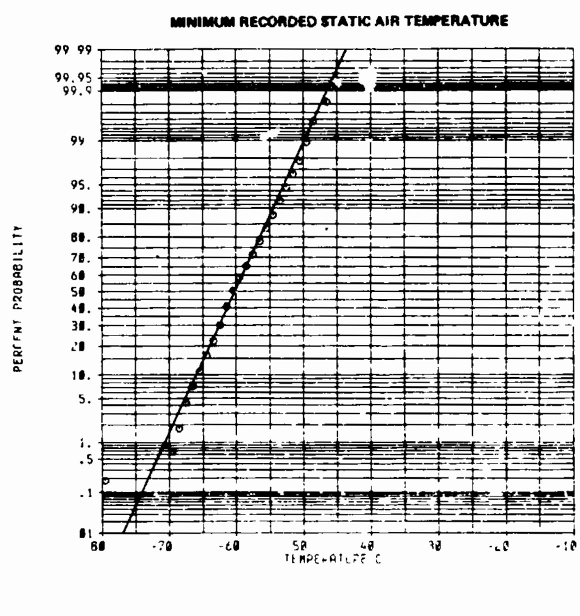


Figure 20.—All Western United States—Tokyo Flights

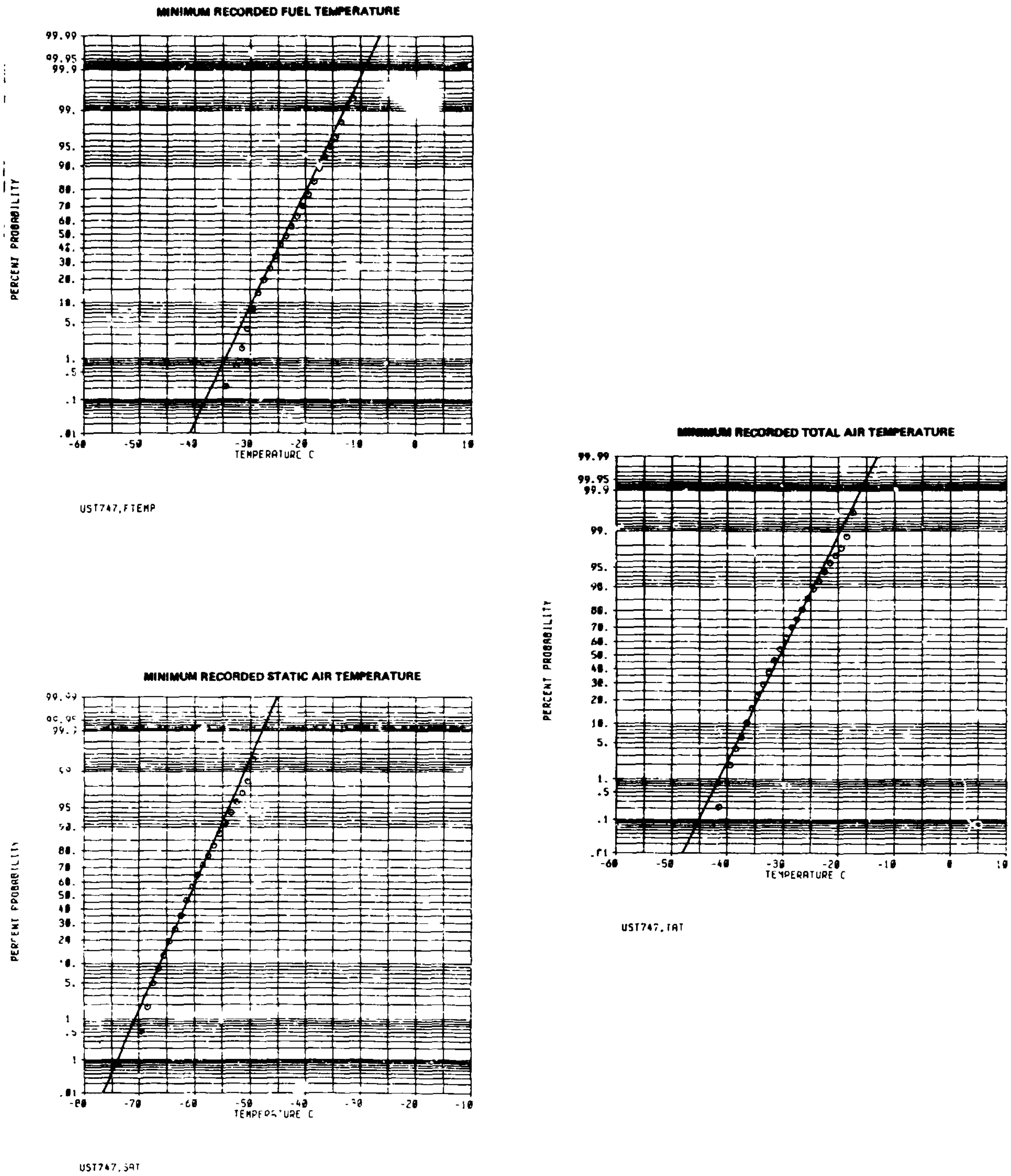
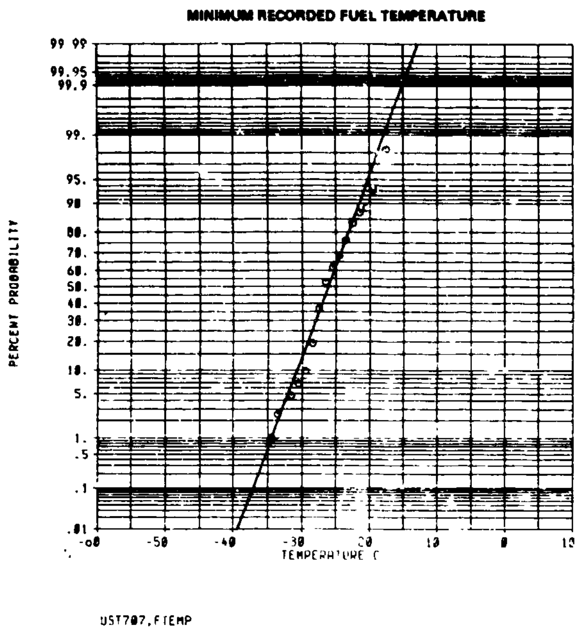
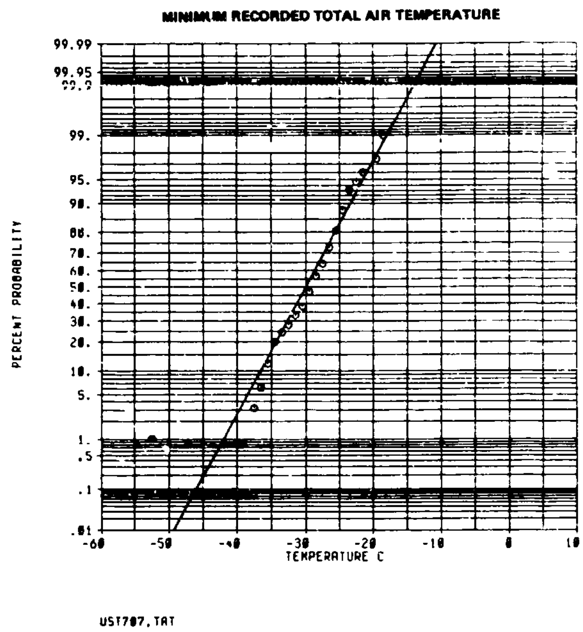


Figure 21.—747 Western United States—Tokyo Flights





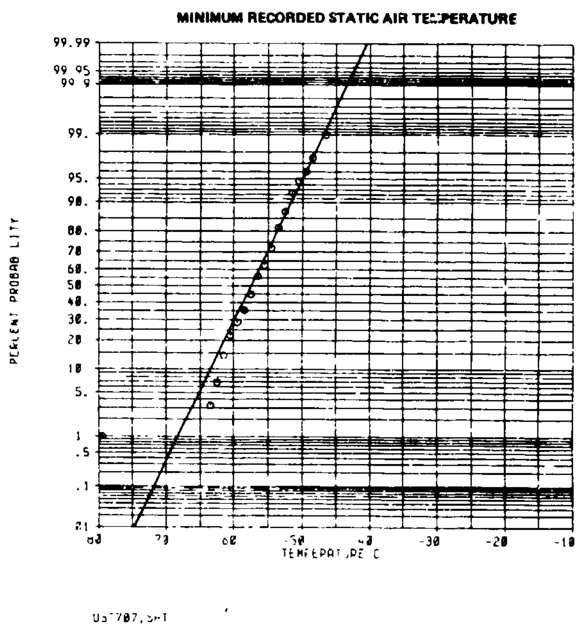
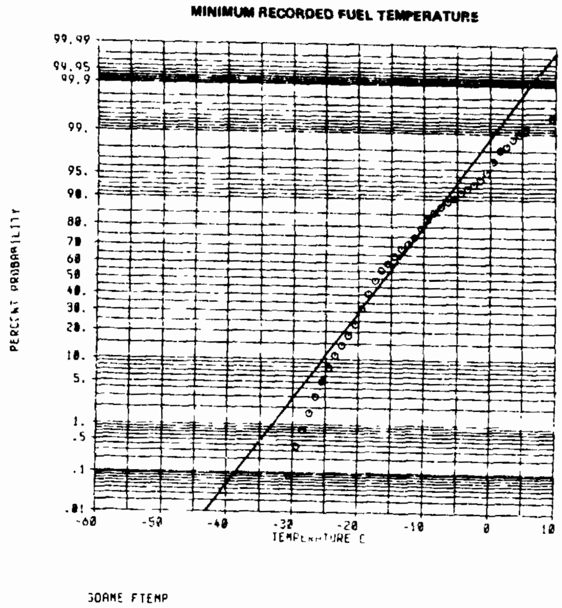
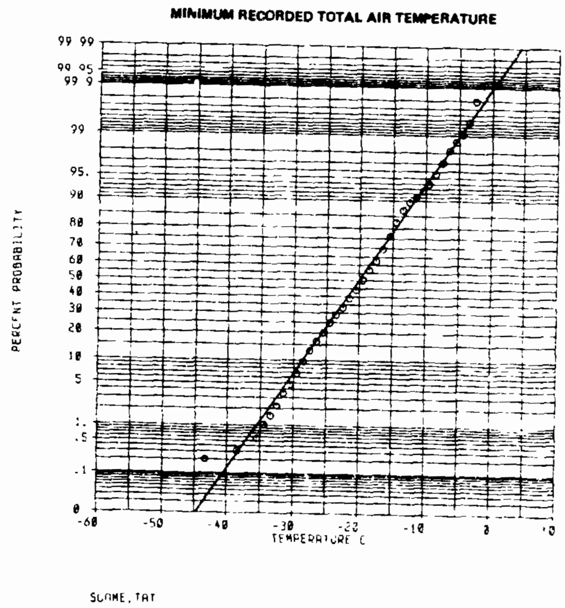


Figure 22.–707 Western United States–Tokyo Flights





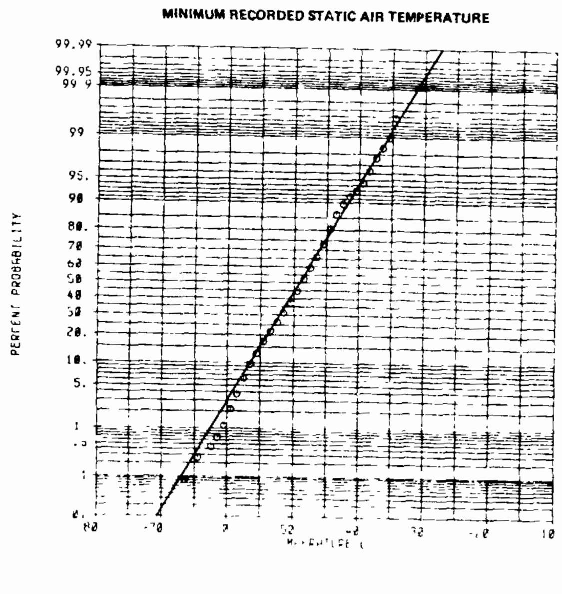


Figure 23.—All South America—Europe Flights

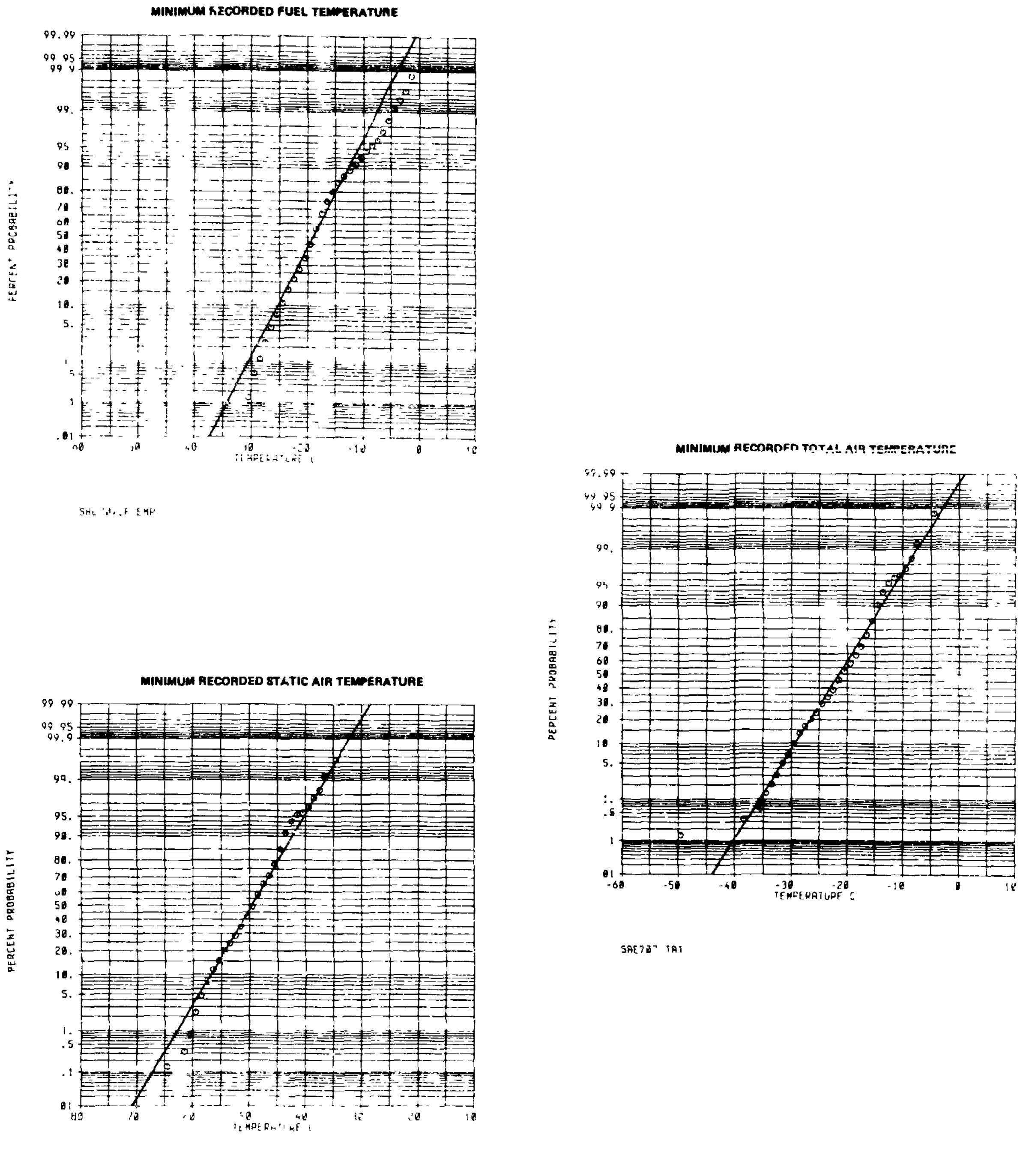
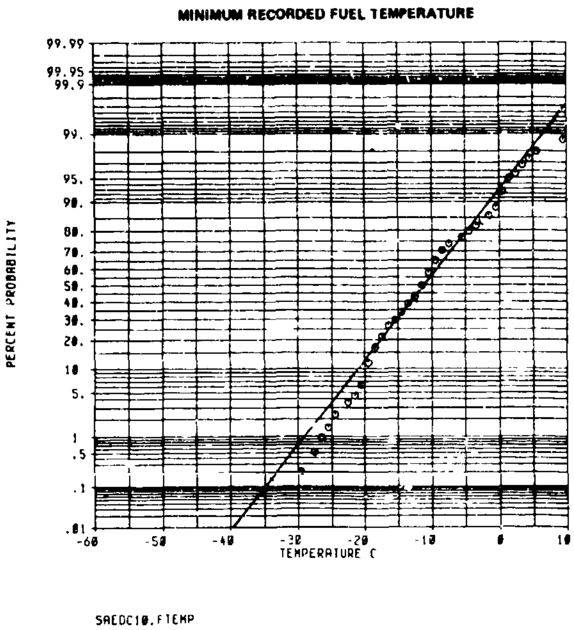
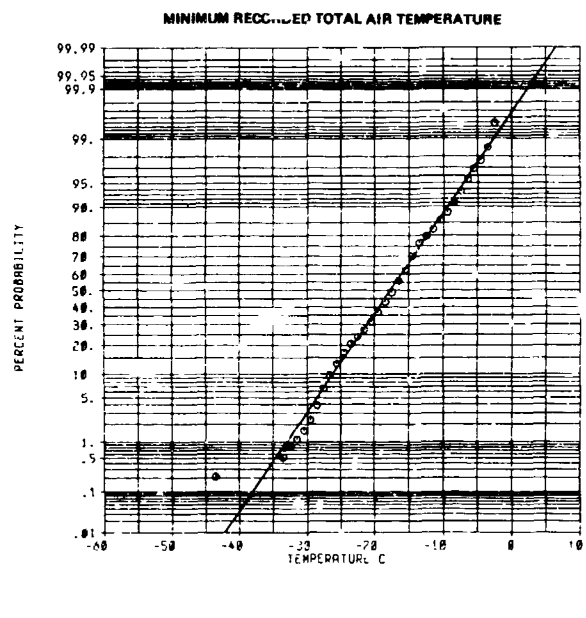


Figure 24.—707 South America—Europe Flights





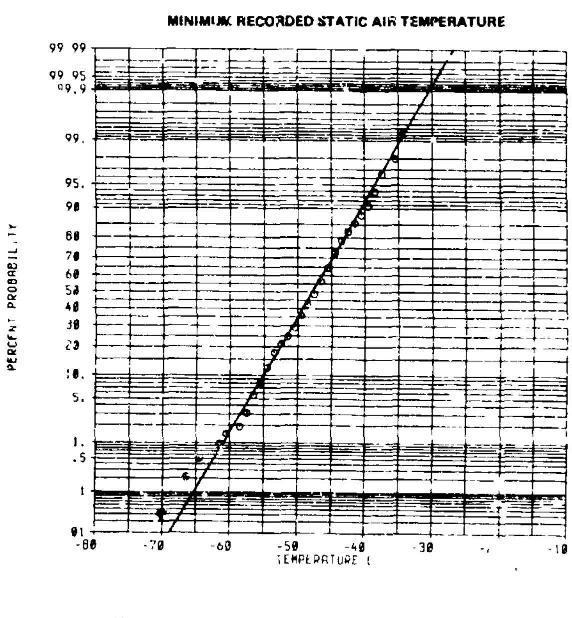
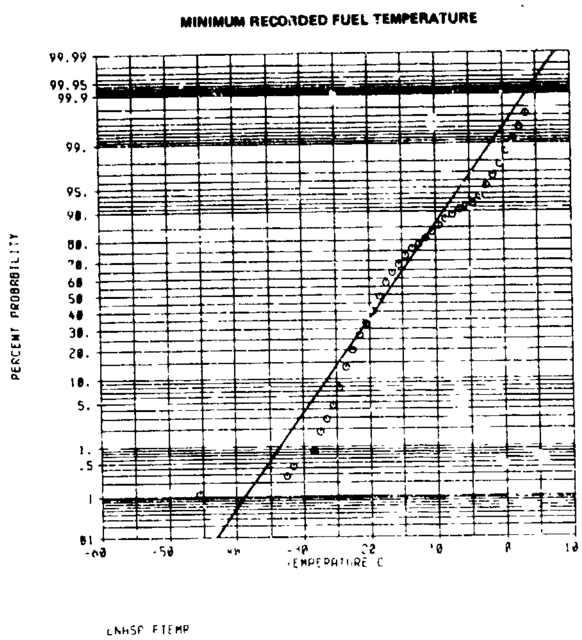
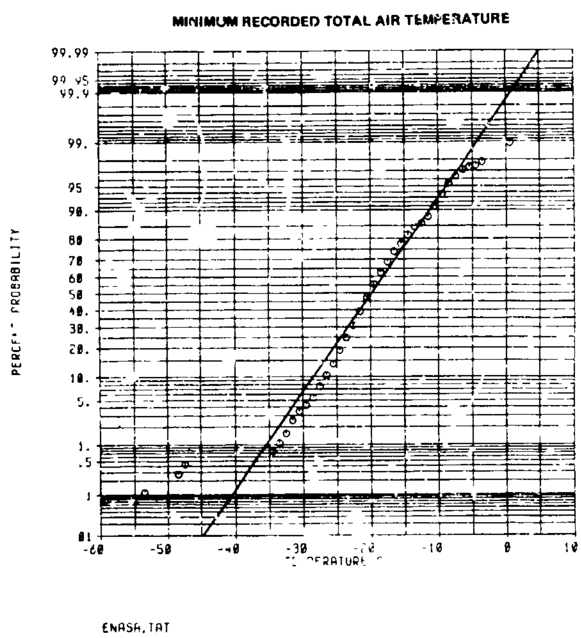


Figure 25.—DC-10 South America—Europe Flights





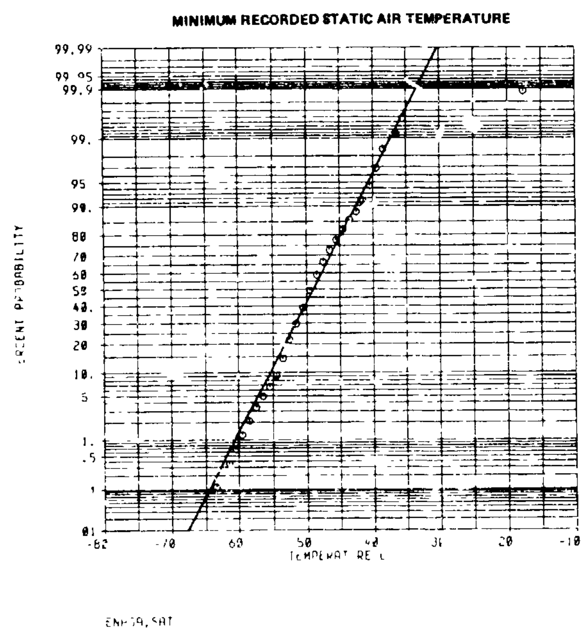
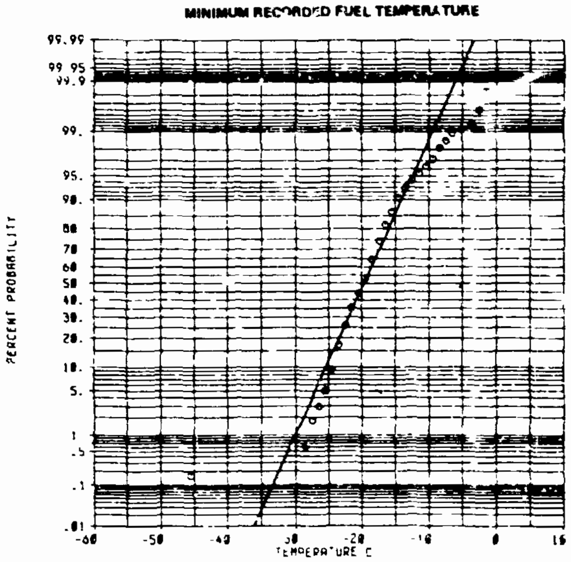
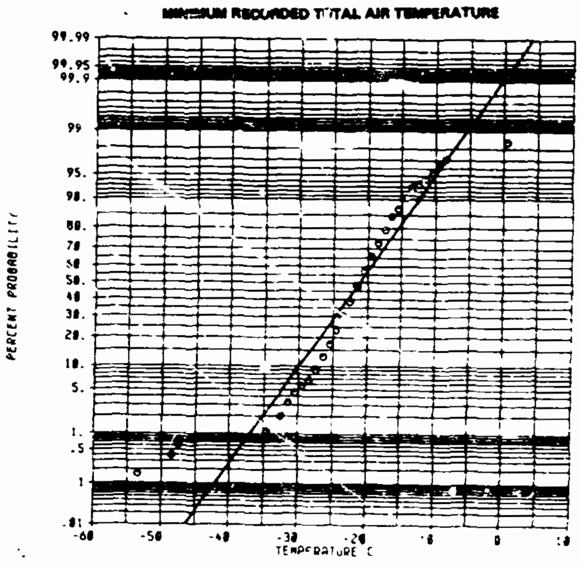


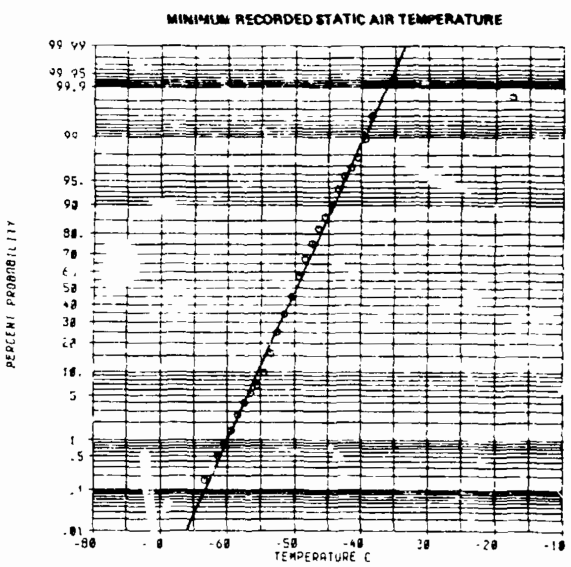
Figure 26.—All Eastern North America–South America Flights



ENS707.FTEMP

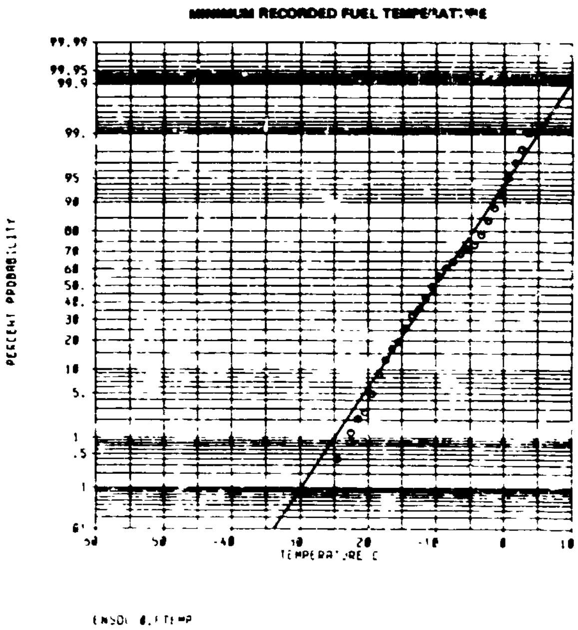


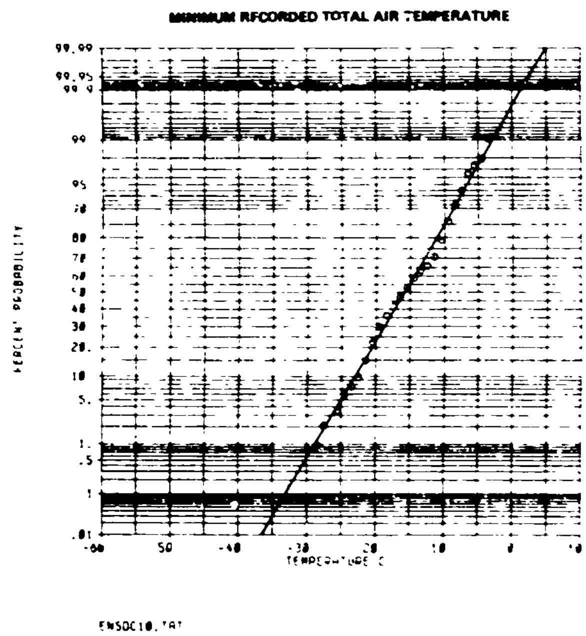
ENS707.TAT



ENS707.SAT

Figure 27.–707 Eastern North America–South America Flights





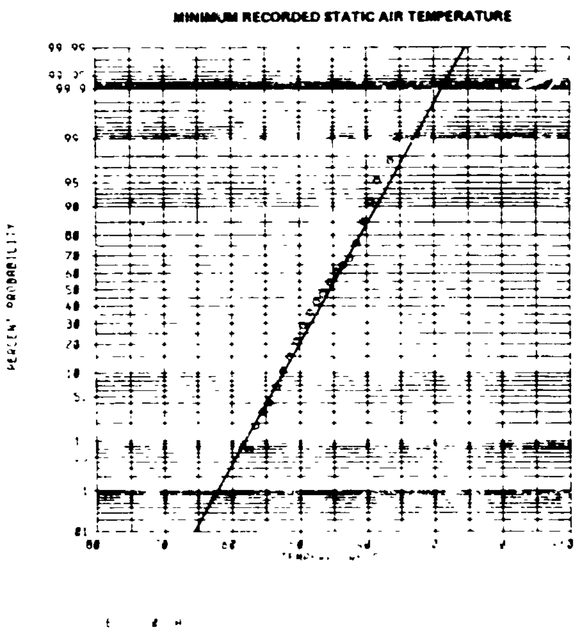
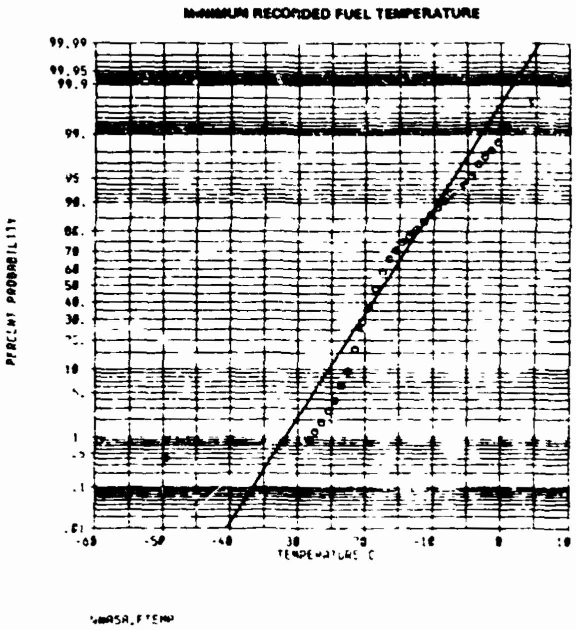
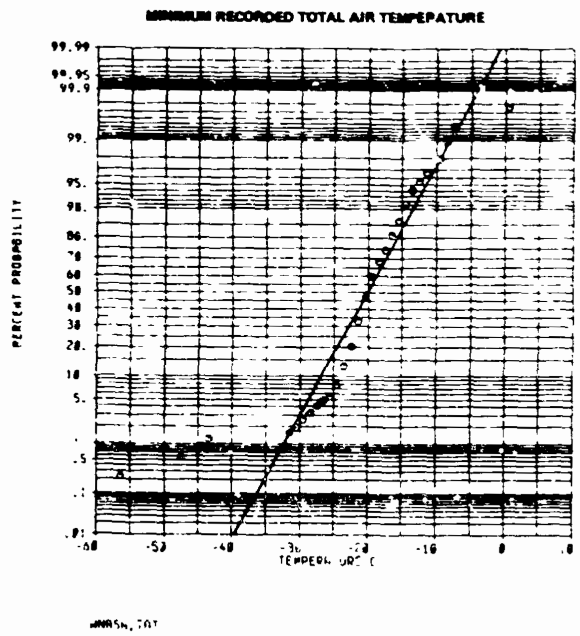


Figure 28.—DC-10 Eastern North America—South America Flights





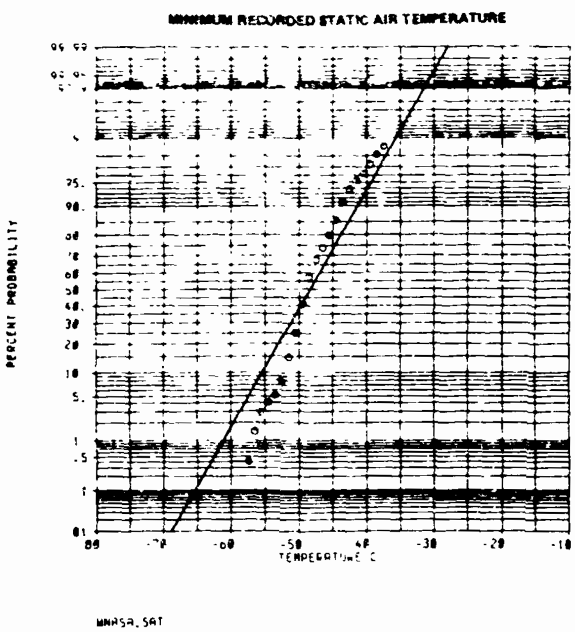
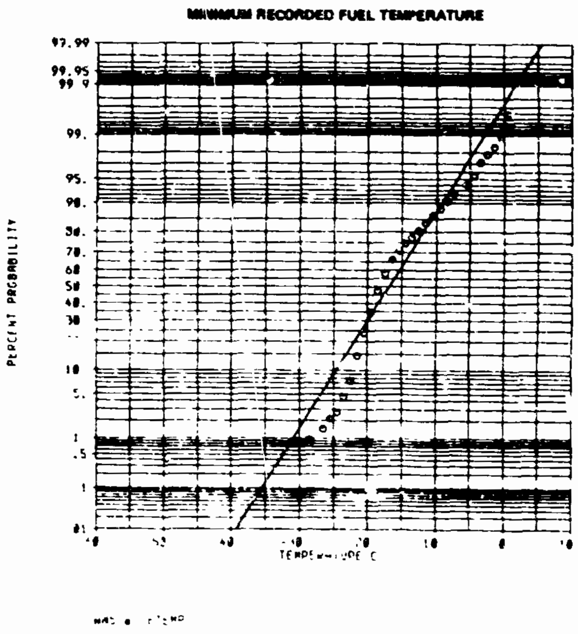
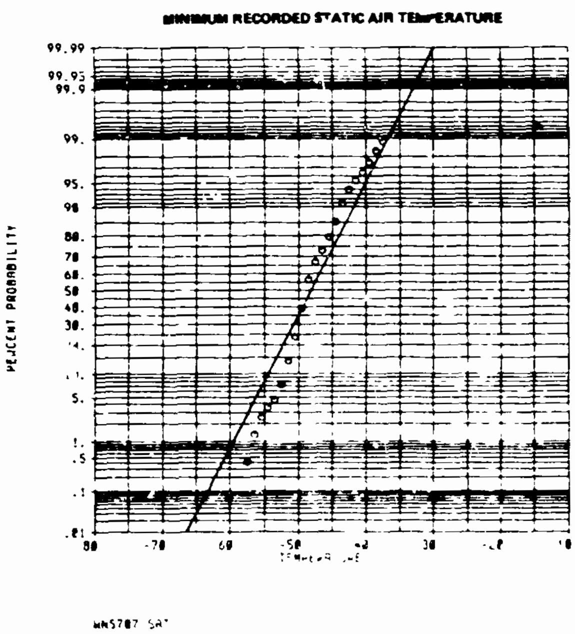


Figure 29.—All Western North America—South America Flights





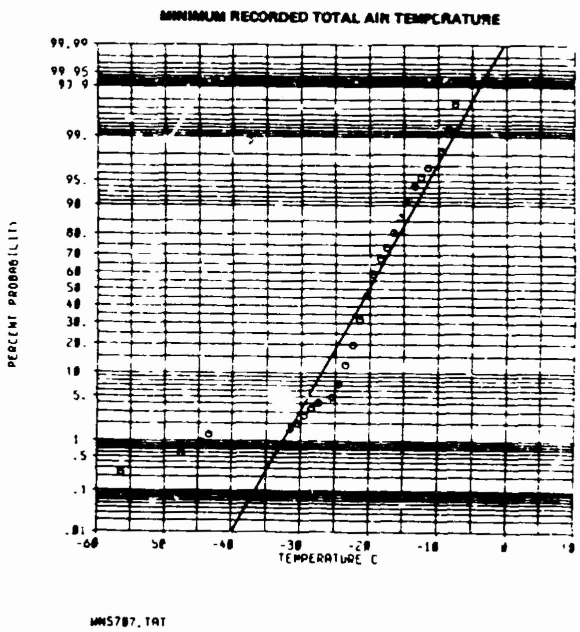
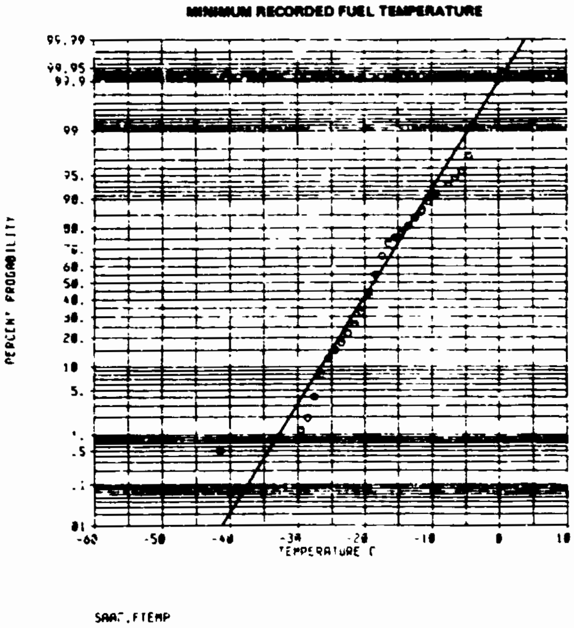
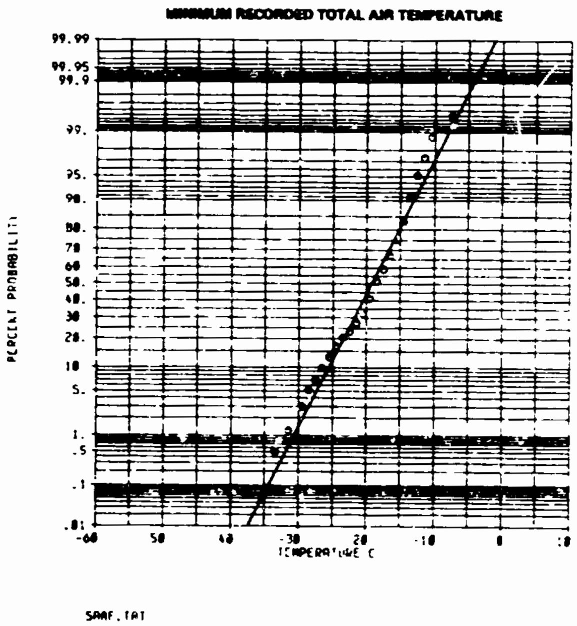


Figure 30.—707 Western North America—South America Flights





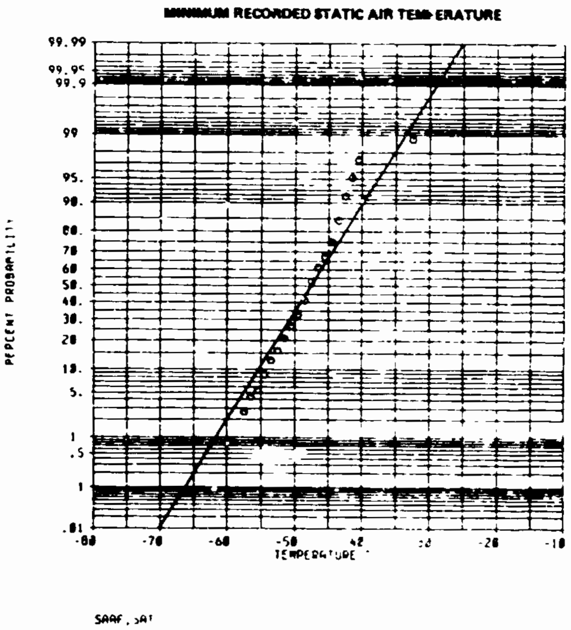
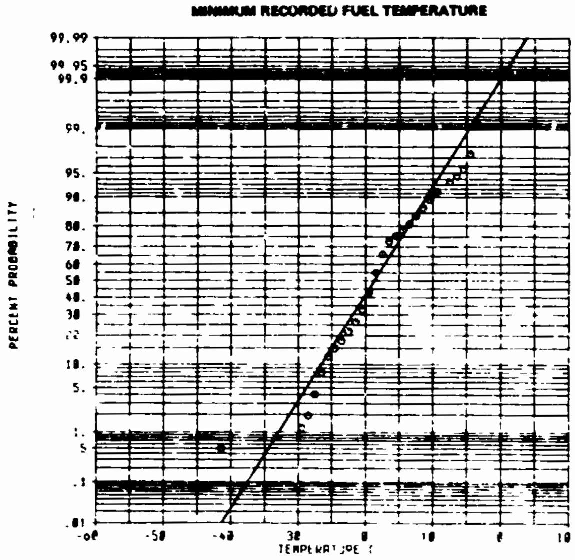
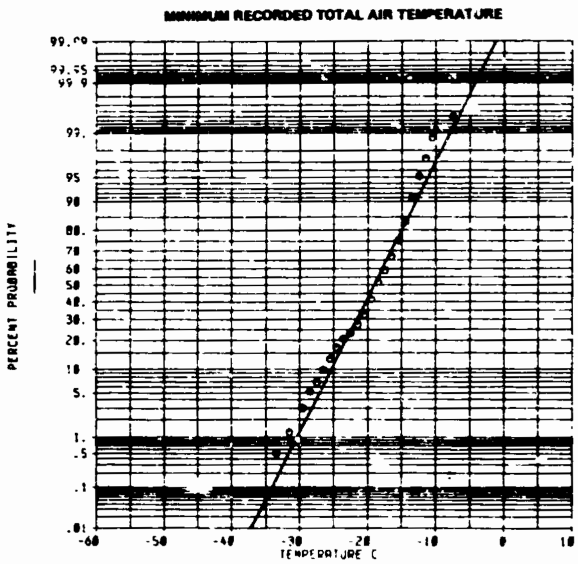


Figure 31.—All South America—Africa Flights





SAF707.TAT

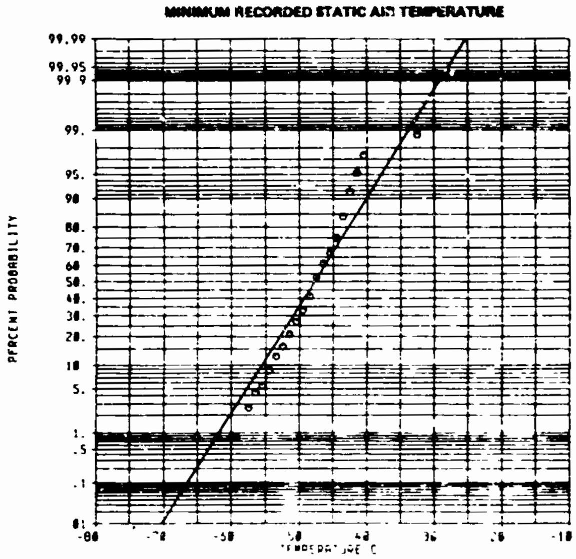


Figure 32.—707 South America–Africa Flights

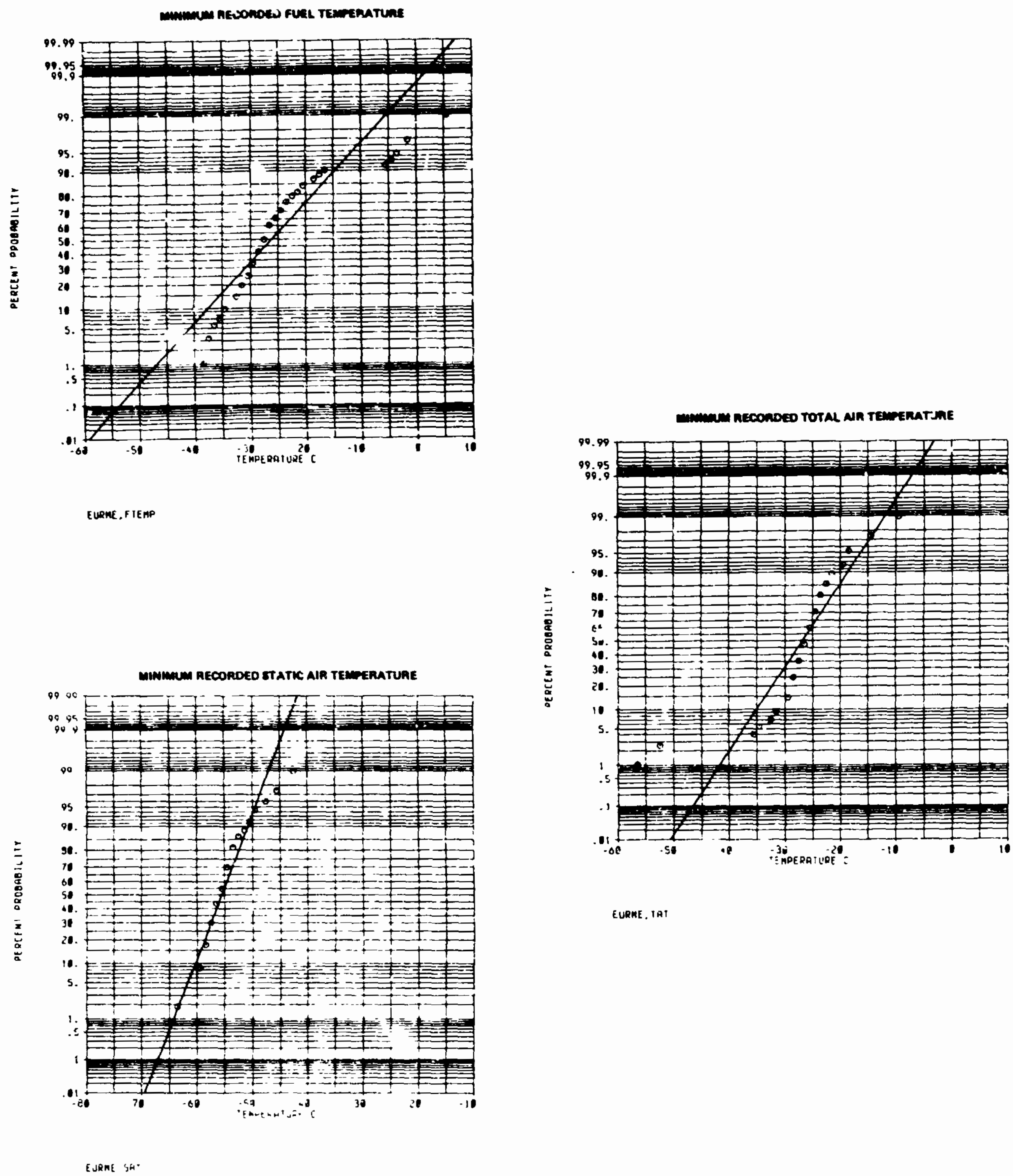


Figure 33.—All Europe—Middle East Flights

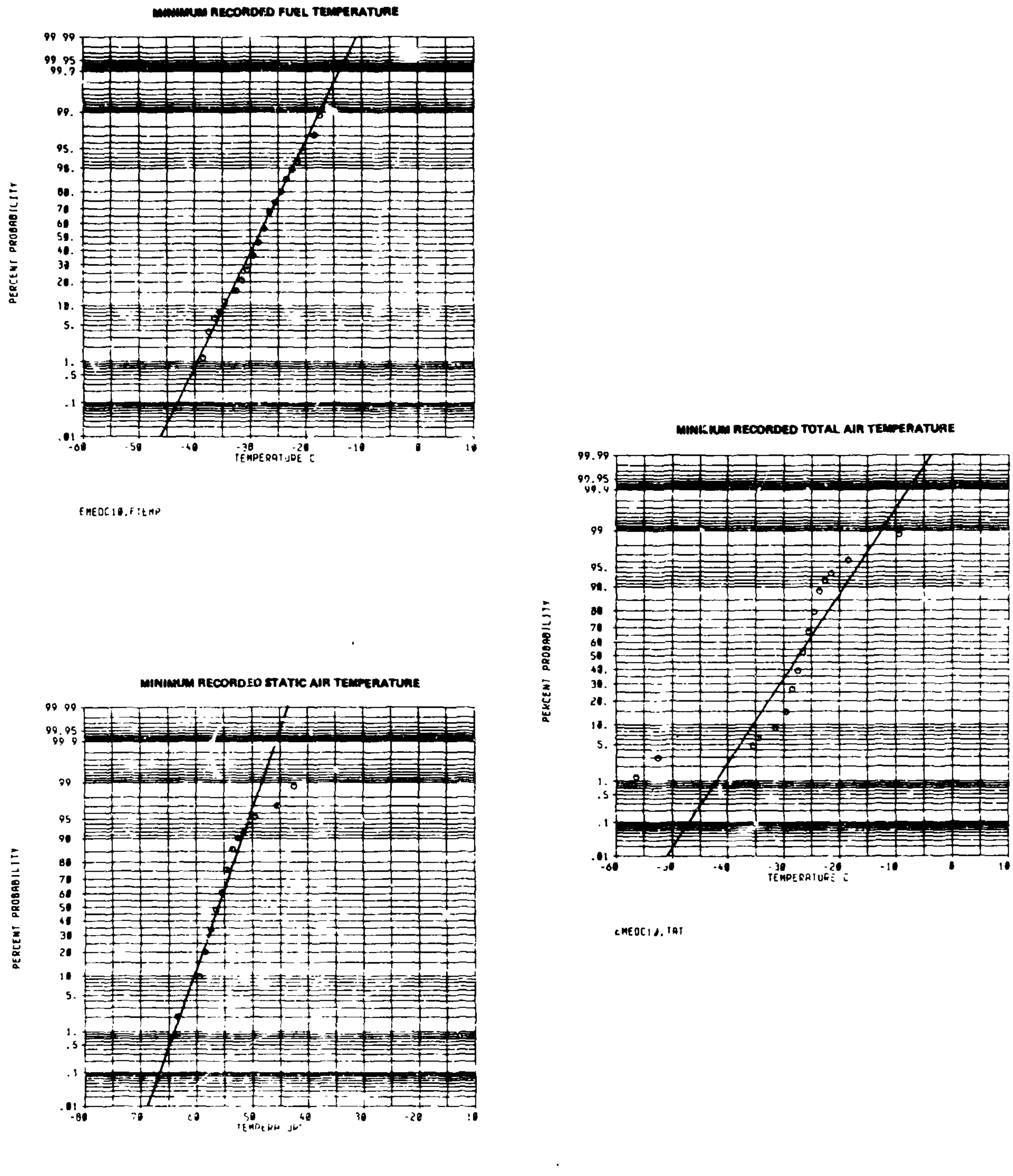


Figure 34.–DC-10 Europe–Middle East Flights

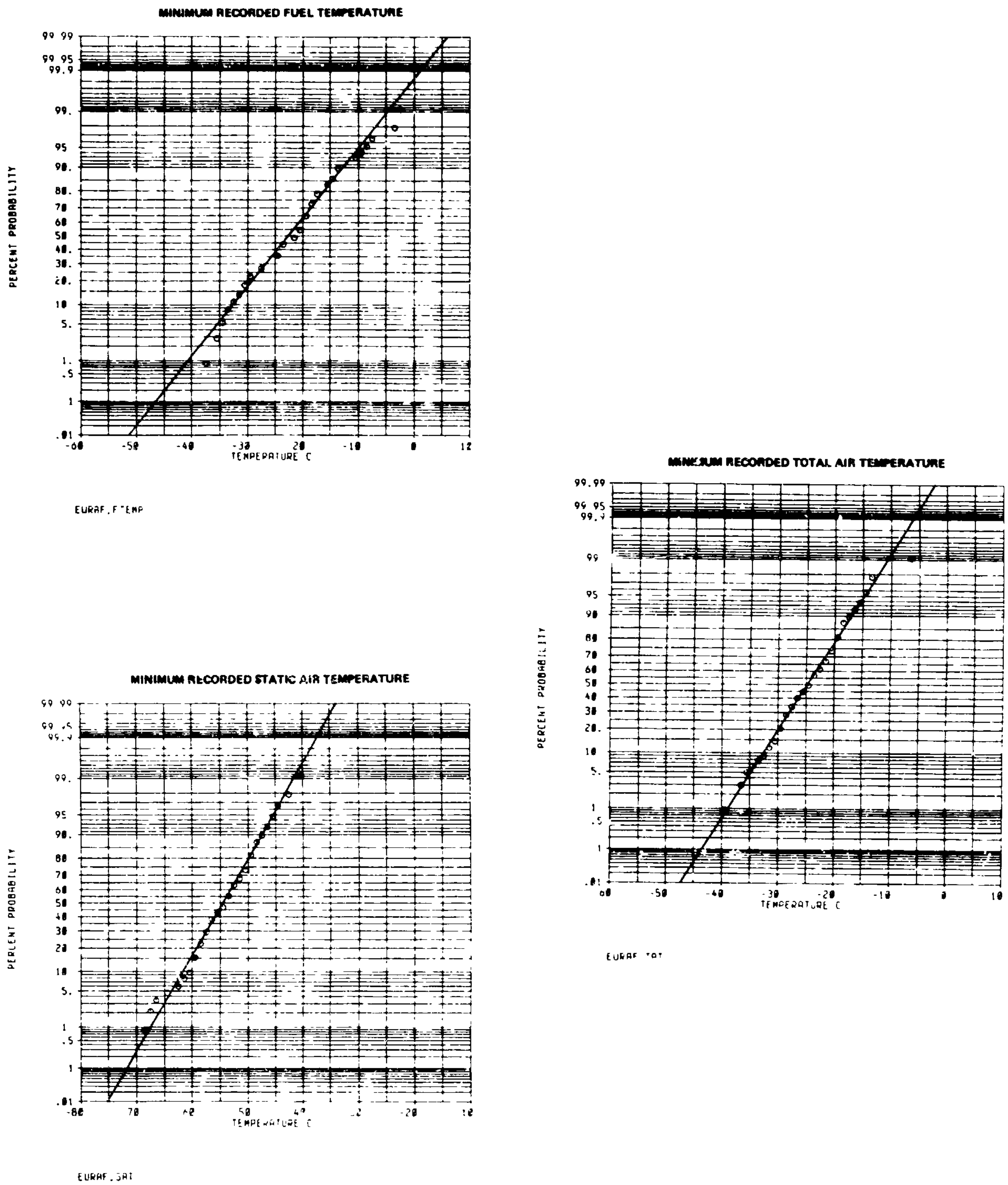
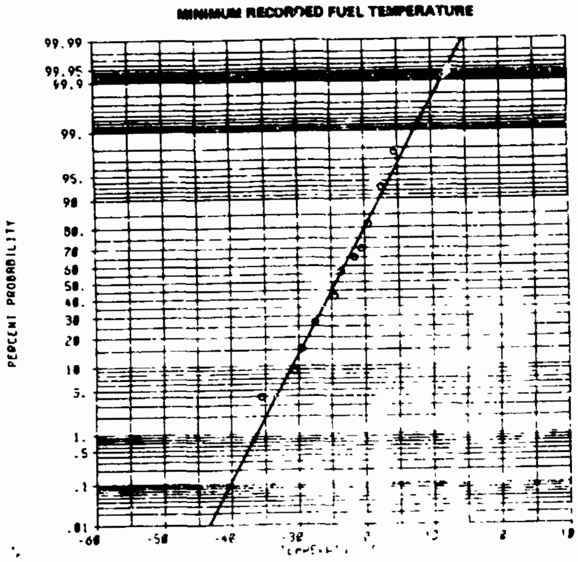
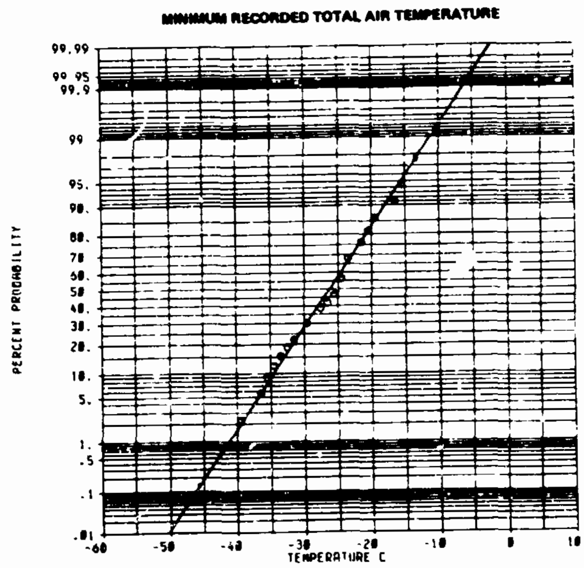


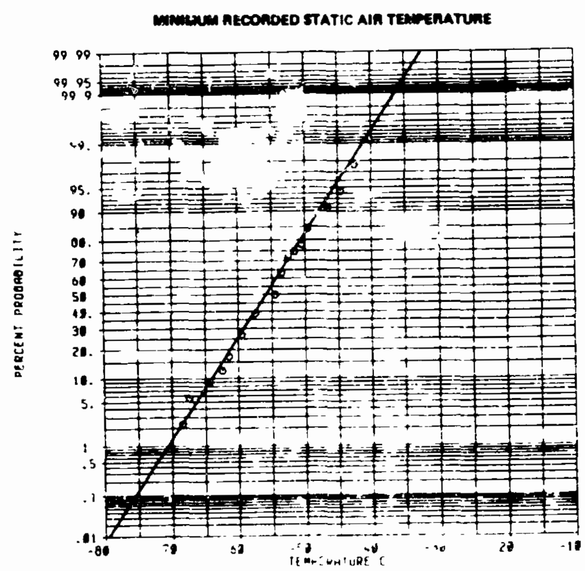
Figure 35.—All Europe–Africa Flights



EAF707.FTEMP

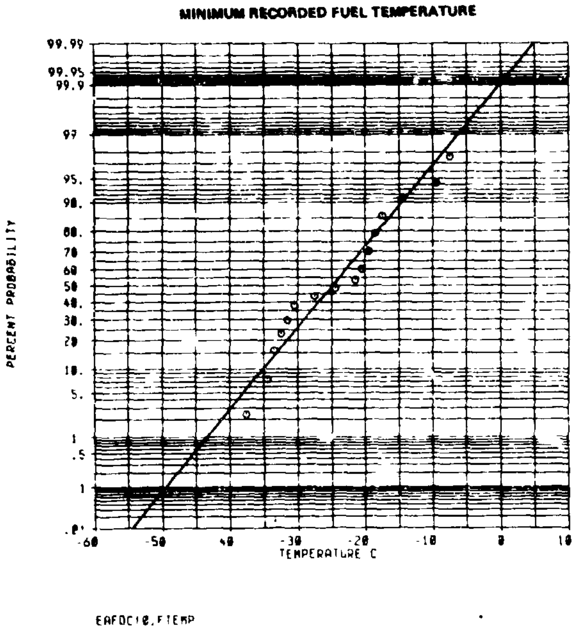


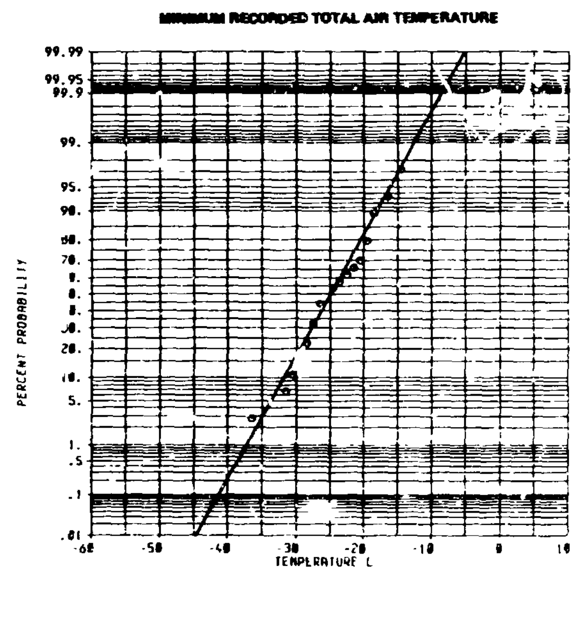
EAF707.TAT



EAF707.SAT

Figure 36.—707 Europe–Africa Flights





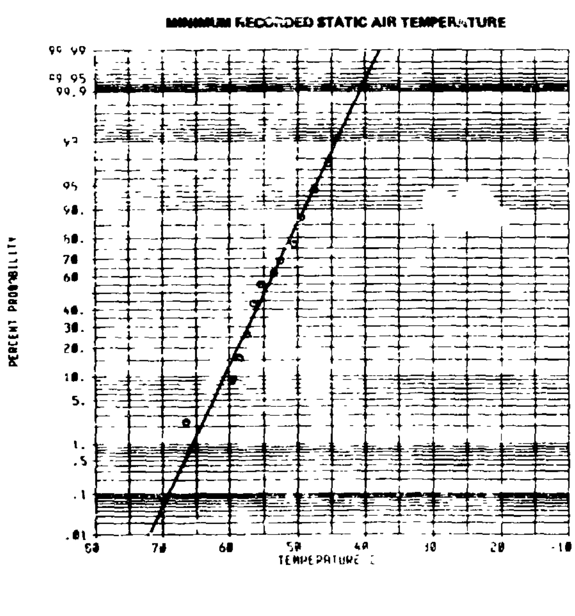
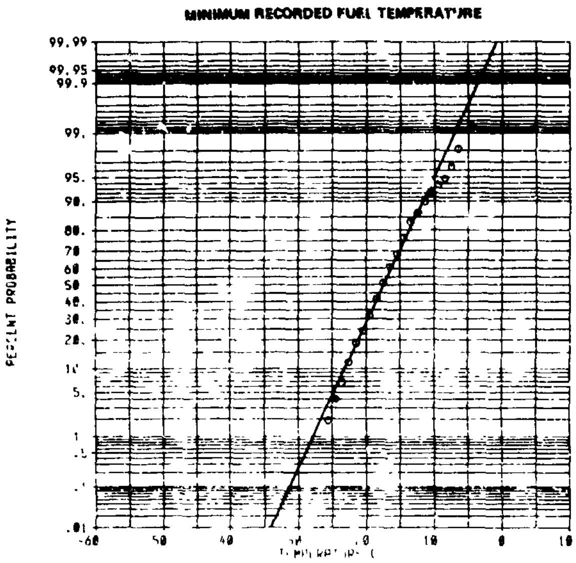
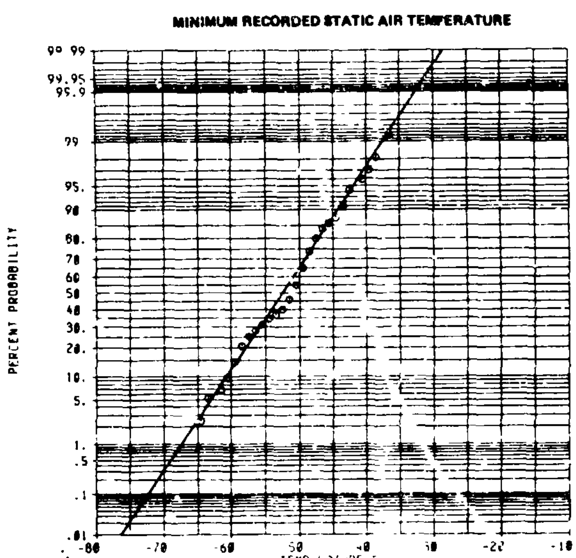


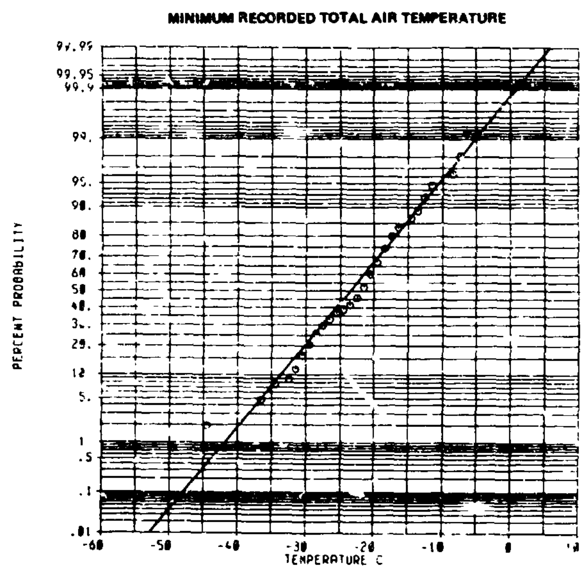
Figure 37.–DC-10 Europe–Africa Flights



PACIFC,FTEMP

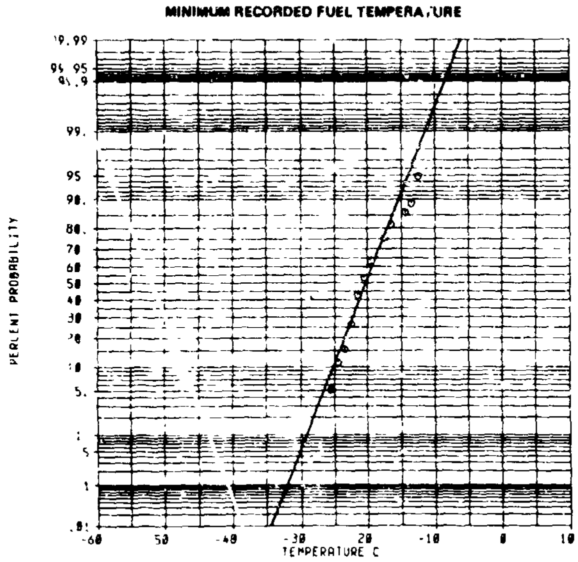


PACIFC,SAT

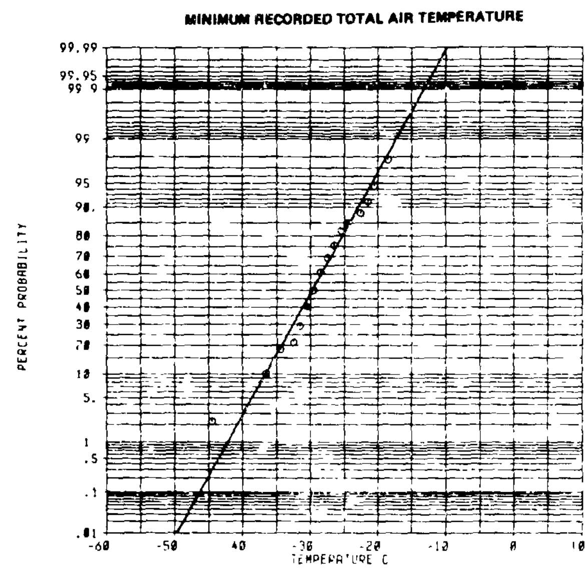


PACIFC,TAT

Figure 38.—All Pacific Flights



PHC747 FTEMP



PAC747.TAT

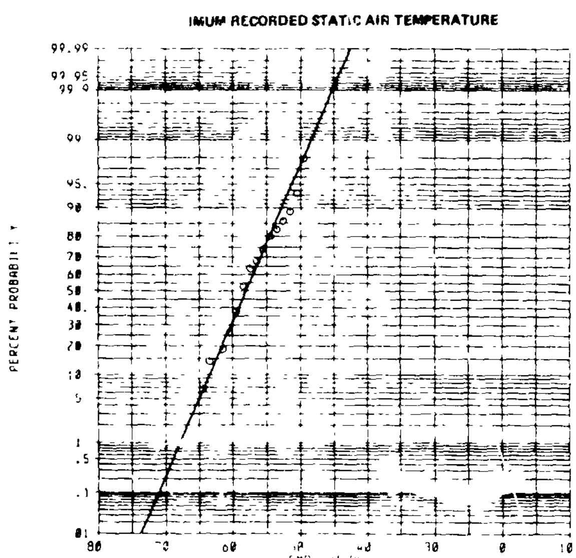
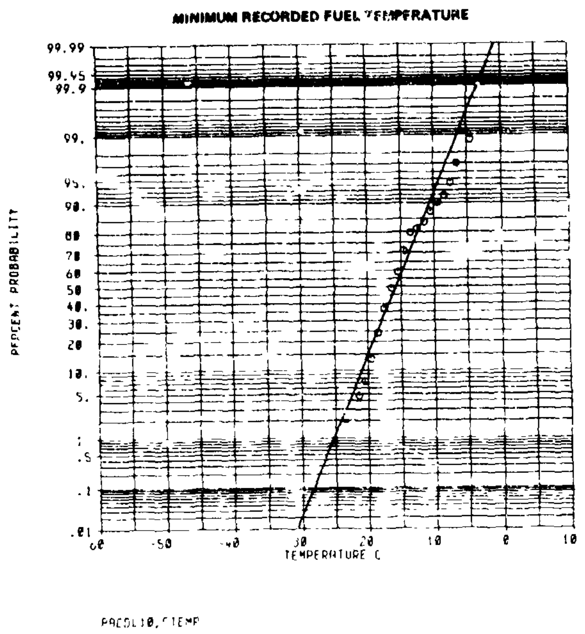
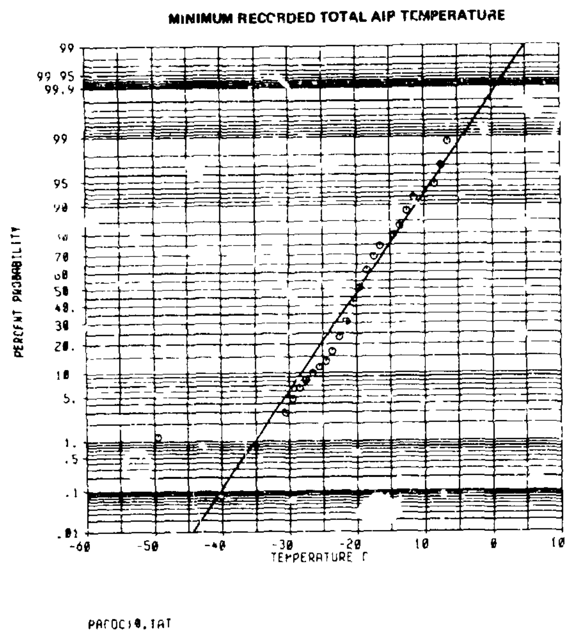


Figure 39.–747 Pacific Flights





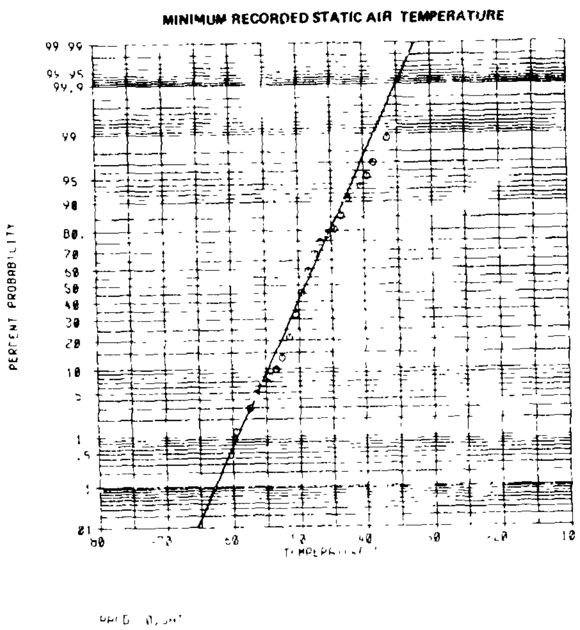


Figure 40.--DC-10 Pacific Flights

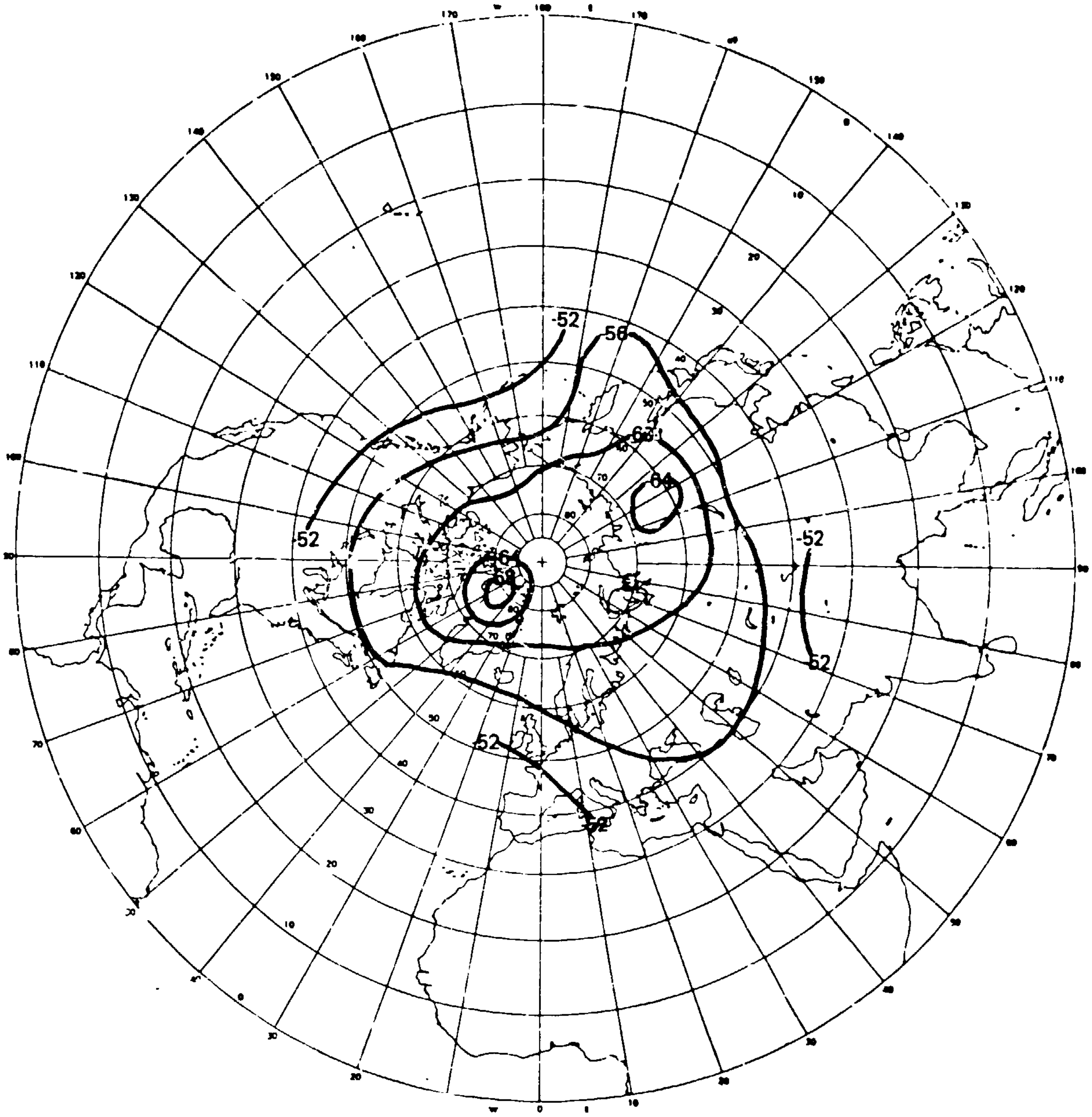


Figure 41.—One-Day-Per-Year Extreme Minimum Ambient Temperature at 9 km (30 000 ft)

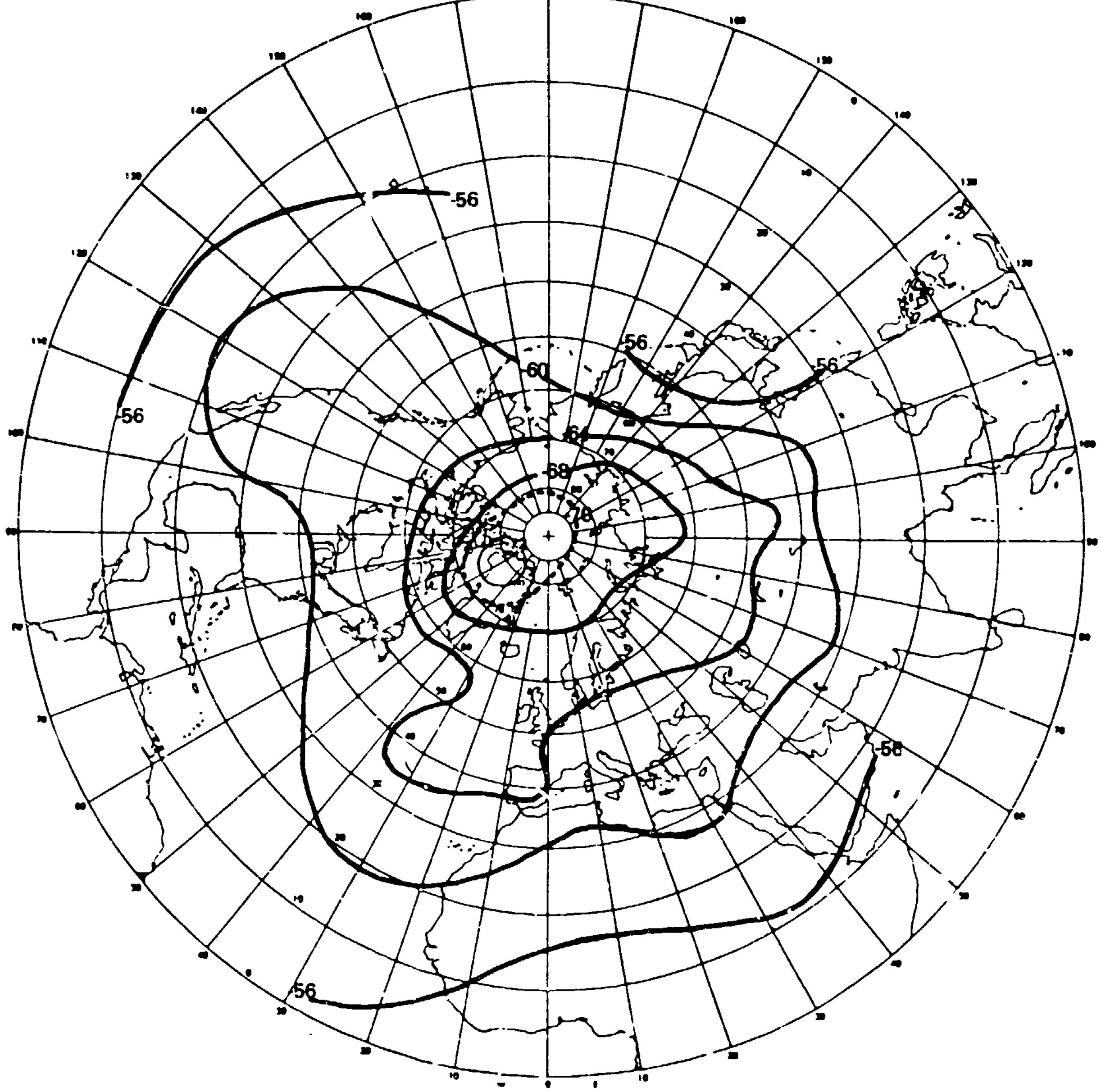


Figure 42.—One-Day-Per-Year Extreme Minimum Ambient Temperature at 12 km (40 000 ft)

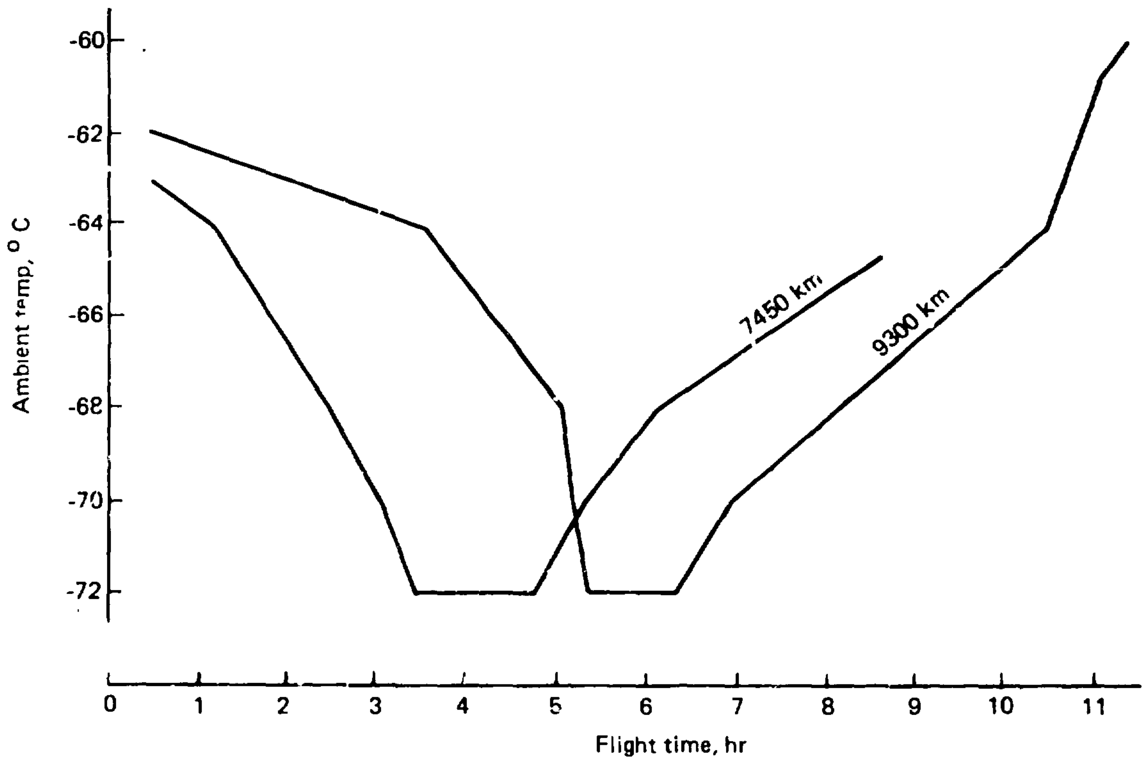


Figure 43.—Minimum Ambient Temperatures (0.3% Probability)

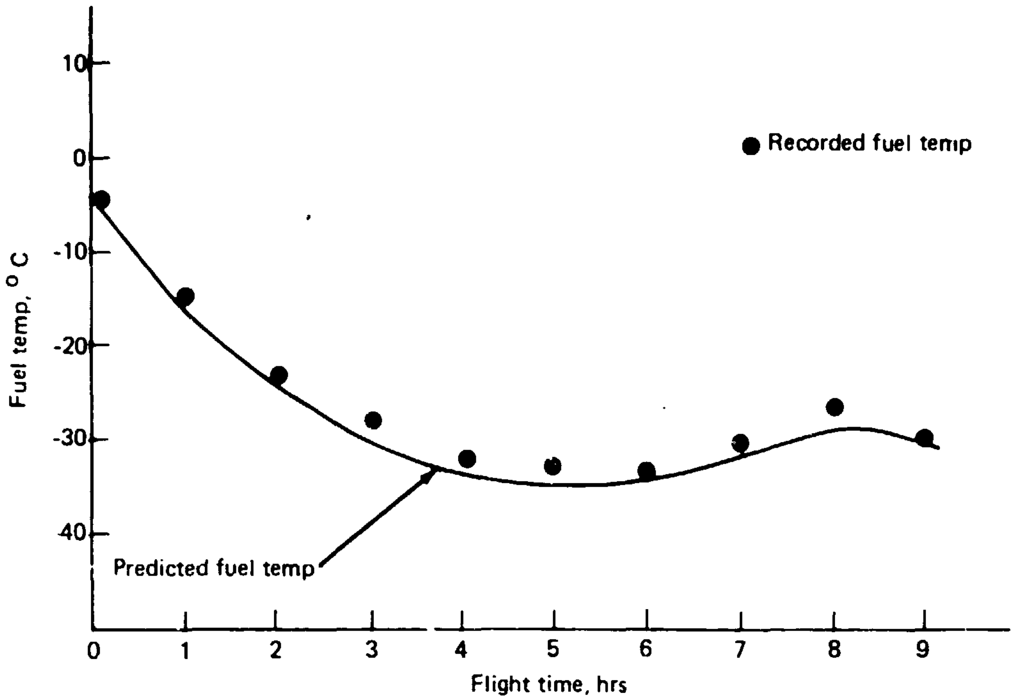


Figure 44. –747 Fiight

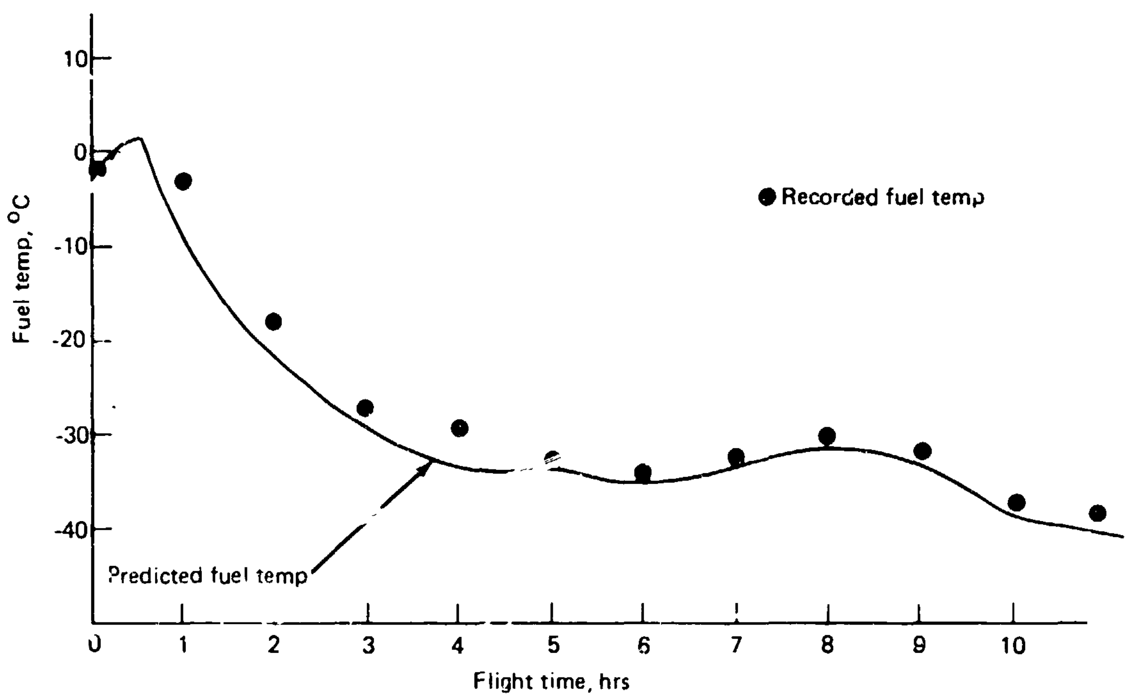


Figure 45.–707 Flight

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2. Crutcher, H. L., and Meserve, J. M., *Selected Level Heights, Temperatures, and Dew Points for the Northern Hemisphere*, NAVAIR 50-1C-52, dated September 1966.

3. Pasion, A. J., Thomas, I., *Preliminary Analysis of Aircraft Fuel Systems for Use With Broadened Specification Jet Fuels*, NASA Report CR135198, 1977.